

# Highly Distributed Data Acquisition on Wind Turbines

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Since inland locations for wind turbines are mostly near populated areas, noise emissions have to be reduced to a minimum. These usually originate from rotating or vibrating parts. By applying accelerometers, microphones, and rotation sensors, it is possible to correlate relevant quantities, determine transfer functions and locate possible sound sources. To achieve meaningful results, data must be collected at the nacelle, on the blades, the rotor, the tower itself and at various positions at ground level. Due to the size of a wind turbine, sensor application is rather difficult, since cable lengths should be kept short for high signal quality. Wiring distant positions is also quite costly. Moving parts, such as the rotor, do not allow fixed wiring or a connection between distant locations. Further, the effects of environmental conditions, like streets, streams or even animals, have to be taken into account for an exact determination of noise emissions. It seems reasonable to independently collect data at distributed measurement positions and use a WLAN for data transfer. This allows a very flexible setup and still achieves phase synchronization by using fiber optical cables or a highly precise GPS clock.

Wind energy is frequently considered a significant option for the transition to regenerative energy sources. Due to the dependency on wind for operation, possible inland locations are quite limited and often quite near populated areas. Noise created by a turbine obviously influences the surrounding environment and could disturb residents nearby. So emitted noise has to be kept as low as possible, which is regulated by various standards, such as IEC 61400-11 in Europe. These usually describe the measurement method, including applied sensors, sensor positions, and the analyses that have to be executed. Currently the focus is on sound power, third octaves and tonalities computed at various so-called wind bins. The complex measurement task has to consider environmental conditions, such as wind speed and direction, the topography and challenges in setting up the measurement system.

Nevertheless, it seems reasonable to utilize sensors to determine noise sources. It is possible not only to determine whether a wind turbine fails to fit required standards, but also determine where alterations in the design have to be made. While the standard setup uses only a few sensors and does not depend on phase synchronization due to the alignment of averaged values with 60 sec averaging time, an advanced R&D setup requires a far more complex measurement setup.

Since significant distances have to be covered to measure vibrations, rotational speed and emitted sound, the measurement setup can be costly and time consuming. Furthermore, surrounding areas near the wind turbine, along with streets, streams, buildings and animals, have to be considered and eventually accommodated during the setup itself. Unfortunately, the setup also depends on environmental conditions, such as wind direction and gondola position, which do not allow a fixed setup and require frequent changes in the worst case. All analyses require a sufficient amount of data for each wind bin and each operational mode. Otherwise it would not be possible to sufficiently correlate unwanted effects to their causes. This requires a rather flexible system, allowing for rapid changes of the setup and a smart data organization supporting the user to finish the task quickly.

We first give a brief overview on the measurement setup required by the IEC 61400 and suggest some extensions for research and development, where possible noise sources are taken into account. Challenges with the standard and extended setup are then addressed, where both technical and environmental aspects are covered. Possible approaches for a highly distributed setup

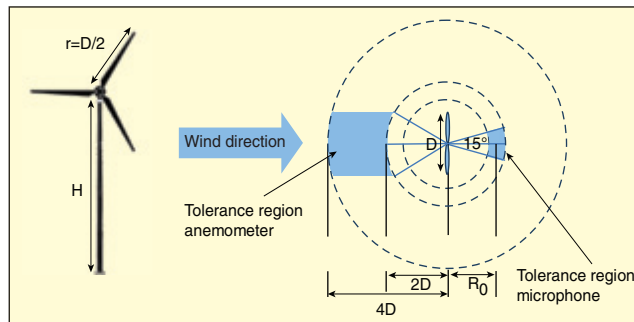


Figure 1. View of basic measurement setup in accordance with IEC 61400; possible locations for microphone and anemometer indicated in blue.

are then presented; this enables the gathering of distributed data and also makes it easy to setup. There is also a short conclusion of the presented solutions, where we offer possible developments in the future.

**Measurement Setup.** The IEC 61400 requires a very strict measurement setup, regulating applied sensors, sensor positions, and dedicated analysis. The analysis usually requires measurements of operating noise corrected by background noise at the same microphone position. So only the operating noise is taken into account without disturbing environmental noises.

The measurement setup is straight forward and is illustrated in Figure 1. Microphone and anemometer positions depend on the hub height  $H$  and the diameter of the rotor  $D$ . The optimum distance between tower and microphone is given by:

$$R_0 = H + \frac{D}{2} \pm 20\% \quad (1)$$

while the microphone is positioned in a 15% corridor behind the gondola. If the wind direction and gondola positions change, the microphone has to be repositioned and a new background noise measurement has to be acquired. The anemometer is positioned between  $2D$  and  $4D$  within the corridor:

$$\beta = \frac{z - z_{ref}}{H - z_{ref}} (\beta_{max} - \beta_{min}) + \beta_{min} \quad (2)$$

at a height of approximately  $z = 10$  m if possible and  $z_{ref} = 10$  m. Furthermore, data monitored by the wind turbine itself, such as weather data at hub height, rotational speed, pitch, gondola position and produced electrical power, have to be taken into account. While it seems obvious to record the noise during the operation of the turbine (*ON* – operation noise), an additional background noise *BG* recorded at the exactly same position when the turbine is turned off, is required to be able to eliminate environmental influences. These can be other turbines located nearby, streets, wind, rivers, etc., that must not be taken into account within the analysis step.

**Extended R&D Setup.** While the previously described method is used to evaluate a wind turbine and judge whether it passes or fails the ordinances, it is inevitable to determine sound sources during the development process or after an installed turbine fails the evaluation. So it seems reasonable to measure possible sound sources simultaneously, which can be correlated to wind bins, where the analyses show high sound powers or perceptible tones.

Most of the sounds are usually generated by moving parts, such as the blades, gear box and tower itself. Here both rotational speed and vibration have to be considered as possible noise sources.



Figure 2. Possible positions for additional accelerometers, microphones and rotational sensors.

Although microphone arrays can be used for sound localization,<sup>2</sup> their use is frequently dismissed due to the effort and cost in the design and construction of an array. Its dimensions have to be quite large to cover low frequencies and sufficient resolution. Most arrays are only capable of determining whether the noise is emitted by the gondola or the blades; this does not represent sufficient information for troubleshooting or possible redesign. So other solutions need to be determined, and we suggest further sensor positions on gondola, blades and tower, as shown in Figure 2. These include accelerometers, which will support noise source direction and the determination of possible transfer paths.<sup>3</sup> Further, these can be aligned to the recorded sounds and be included in the frequency analysis. The gondola is further equipped with additional microphones, which can be correlated easily to the distant microphone. In a last step, the gearbox is equipped with sensors picking up rotational speed, allowing the correlation of frequencies in air- and structure-borne vibrations to the current operating state of the wind turbine. In total, an additional number of 10 microphones, two rotational sensors and 60 accelerometers are used to analyze the wind turbine in depth.

### Measurement Setup Challenges

It is commonly agreed that meaningful measurements require suitable measurement positions. While it frequently seems easy to determine points of interest, it is a challenging task to collect the data from varying points simultaneously. Both technical and environmental issues have to be overcome to conduct a reliable measurement.

**Technical Issues.** Technical issues with cabling need to be addressed first. An old rule of thumb states that the distance between sensor and measurement frontend has to be kept as short as possible. Various reasons lead to this assumption. Cables and cabling cost money. To achieve a high signal quality and keep the signal to noise ratio (SNR) high, quality cables must be used. Furthermore, it is quite laborious to apply sensors at distant positions and connect these with a centralized frontend.

In addition to economic reasons, signal quality has to be taken into account. Various sensors can be used with a very limited cable length. Table 1 shows some selected maximum cable lengths. Although ICP® and microphones can be driven with long cables without problems, others have by far shorter, especially for charge sensors and strain gages. Obviously, typical lengths are much shorter than an average wind turbine with a hub height of approximately 100 m and an average blade of 73 m length. So it is necessary to find a suitable solution for each applied sensor.

Table 1. Maximum cable length for selected sensors.	
Sensor Type	Max Length, m
Microphones	100
ICP®	100
Strain gages	10
Hot strain gages	5
Charge	15

It is often not possible to apply cables (between hub and



Figure 3. Influences on measurement setup include trees, roads and neighboring wind turbines.

nacelle, for example), since there are moving parts in-between, and OEMs usually do not install a loop-through for a wide range of signals.

**Environmental Challenges.** Since wind turbines are usually located in public regions, environmental conditions have to be taken into account with the previously mentioned technical limitations. These are primarily influenced by the surrounding topology, as shown in Figure 3, where trees, creeks, streets, buildings or even animals can become obstacles that have to be overcome. All these factors encourage direct cabling to a centralized data acquisition system. Furthermore, wind turbines are usually located in farms, where noise emitted by neighboring plants influences the acoustic analyses.

Obviously, other objects may also disturb the measurements. Therefore, possible sensor positions are even more critical when considering wind speed and direction. Nevertheless, IEC 61400 requires the recording of so-called background noise at each microphone position. This is used to correct the recorded operating noise according to the corresponding wind speed; also the measurement setup has to be flexible to cover all possible combinations of power curves, wind directions and wind speeds. Consequently, both hardware setup and data management have to be designed in an easy-to-handle manner, where little effort is needed to change the required settings.

### Distributed Data Acquisition

Data acquisition of wind turbines requires a specialized system near the points of interest. Such a system not only has to overcome measurement difficulties but also must provide correct data at a reasonable effort and cost. A few possible solutions are presented in the following sections.

**Common Approaches.** Within the last few years, various approaches for distributed data acquisition on wind turbines have been implemented and have been applied in a wide range of applications. Figure 4 illustrates possible setups with differing levels of performance.

The most common setup is shown in Figure 4a, where the analog signals from a wide range of sensors are collected and digitalized by one central PAK MKII frontend. The data are subsequently transferred to a workstation or laptop via LAN or WLAN. Data are stored at a maximum rate of 40 MB/s, corresponding to 48 channels sampled at 204.8 kHz and quantized with 24 bits. The main advantage of a direct link to a PC is the possibility to monitor the measurements and therefore the wind turbine online. Further, it enables the engineer to conduct analyses on line, such as spectra, psychoacoustics, and order tracking, which allows immediate

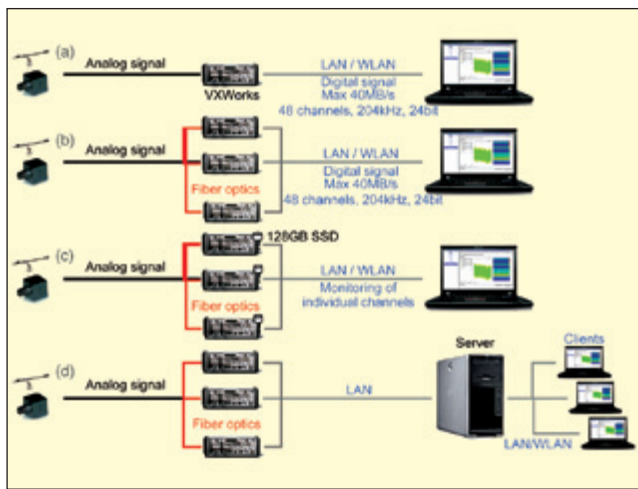


Figure 4. Overview of different approaches for distributed data acquisition. a) Centralized front end and immediate data transfer to a PC; b) Multiple, synchronized front ends and centralized data storage on a PC; c) Cluster of synchronized front ends with local storage and monitoring system; d) Cluster of front ends within a server-client setup, allowing data distribution to selected clients without interference with a current measurement campaign.

conclusions and trouble shooting.

As previously noted, the length of cables, especially for sensors, appears to be crucial. So a first step in a reliable distributed data acquisition system has been implemented by applying multiple PAK MKII frontends, as illustrated in Figure 4b. All frontends can now be placed near the required sensor positions, keeping the length of cables short. The distance between frontends is only limited by the network connection used for data transfer. Applying fiber-optics distances of approximately 1 km have been achieved in operating conditions. Further, it is now possible to increase the channel count, without the need for more powerful controllers. The data digitalized by each frontend is transferred to a central PC. The maximum transfer rate is limited by the network that runs at 40 MB/s.

While a wide range of analyses is not dependent on phase synchronization (alignment of averaged values or the overall level) transfer functions can only be determined correctly in case the data are aligned in phase. Common frontends use individual clocks and therefore sample at slightly varying time stamps. Because of that, a centralized clock is required and distributed via fiber optics, as indicated in red in Figure 4b. This way, a phase error of 0.2% is achieved at a frequency of 10 kHz. With a growing amount of sensors and the desire for high sampling rates, the current maximum data rate of 40 MB/s is the measurement limit.

Therefore, the approach illustrated in Figure 4c is applied for high channel counts and a vast amount of data. Each PAK MKII frontend is now equipped with an internal SSD, the so-called local storage, where the data are stored. A selected number of channels can be transferred to a PC for monitoring and analysis purposes. This way, each individual frontend is able to store 40 MB/s on the internal hard drive, allowing a seemingly unlimited number of channels with sampling rates up to 204.8 kHz.

Phase synchronization is achieved by applying a centralized clock and its transfer via fiber optics. Due to the system's stability and the limited amount of data that have to be transferred to the PC, a direct link through WLAN is also possible. After completing a measurement campaign, the data stored on the single frontends are transferred to a PC via network and merged to one large dataset. This way, the user can work with a single set.

**Server-Client-Based Topology.** To analyze a wind turbine in detail, a large number of sensors is required. All possible wind speeds and power curves have to be captured. With the setup described in Figure 4c, the PAK system enables one to monitor and record data from distributed measurement points over a long period. It is often necessary to access data for other purposes, such as providing data to colleagues from other departments like aerodynamics. Therefore a server-client-based technology has been introduced to allow fast and reliable access to selected data, as shown in Figure

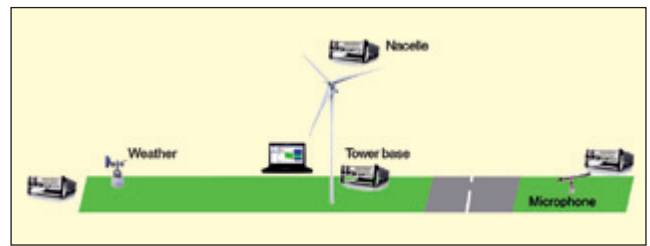


Figure 5. Wireless setup for a measurement campaign on a wind turbine.

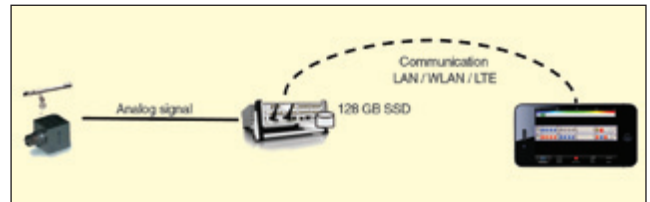


Figure 6. A look into the near future: Individual PAK MKII front ends are monitored with smart devices.

4d. The data acquired by the individual frontends is managed by a central server. Its primary task is to monitor measurements and manage changes in the measurement setup. A secondary task is to distribute data to attached clients. These can be connected during any phase, either at the start of a measurement or even during the measurement itself, and record and analyze the entire data or only a selection of channels of interest.

The server is now capable of fulfilling the client's request or deny it and provide only a specified selection of data. This is important, since not all users should be able to access all relevant operational data of the wind turbine. For example, a consultant for blade design does not necessarily need the currently emitted electrical power and the current rotational speed of the gear box. So data access is limited to a predefined user group.

**Wireless Solution.** The previously described approaches for data acquisition still require at least one cable to each frontend. These are usually Ethernet cables for data transfer and fiber optics for phase synchronization. Although the number of long cables can be kept quite low, and both Ethernet and fiber optics are standardized and affordable cables, these cannot be applied in each situation. Therefore, we suggest an entirely wireless solution (see Figure 5).

All PAK MKII frontends are placed directly at the points of interest, keeping the rest of the cables as short as possible. Applying local storage enables the user to set up a WLAN at the technical limits, since the transferred data are negligible. Only control commands, such as start, stop, or automated range detection, are transmitted. If some of the channels have to be monitored, only the selected ones are transferred without interfering with the measurements. Even if the wireless network fails, the measurements will be continued with full data integrity.

## Conclusions and Outlook

We have provided an overview of current state-of-the-art data acquisition for acoustic analysis of wind turbines. While the setup required by IEC 61400 is only used to evaluate a wind turbine and only considers electrical power, wind speed and sound pressure at predefined positions, we suggest extending the setup to a wide range of additional sensors. These collected data can be subsequently used within the R&D process to determine possibly disturbing tones or high sound power levels. This is usually performed by monitoring rotational speed, acceleration and sound pressure.

Since distances between desired sensor positions are quite long and cabling cannot be handled easily in every situation, a distributed data acquisition system is recommended. PAK MKII frontends can be placed near the sensor location, to guarantee high quality signal and reliable storage on internal hard drives. If required, phase synchronization can be achieved with one additional fiber optic cable.

Further developments and research will take place in the future to enhance the measurements and simplify the setup. As a first step, an entirely wireless solution, where even phase synchronization


is granted, has to be found. Therefore a central clock, which is in sync even over long distances, has to be established. First trials have shown promising results using a GPS clock, which is highly precise, and can be used to trigger time stamps and provide low phase error.

The current setups can be performed rather fast and are flexible, yet they require an expert, because there are various error sources that have to be monitored. Also, it is designed as a “one-man” system, where one operator can set up and monitor the measurements. He also has to observe and detect unusual events in which the measurements have to be triggered. Since the monitoring task is especially exhausting and experts are quite expensive, a remote solution needs to be designed.

As an alternative, parts of the population living nearby could be instructed to trigger the measurement in case of unusual events. Figure 6 allows a peek into the near future. Each PAK MKII front-end is equipped with an additional processing unit and a server. This will provide all the data required for operation and transfer

to a smart device based on iOS or Android. All the controls can be easily performed and only the data required for visualization purposes is transferred to the smart device. This will allow access and monitoring from almost any point in the world, provided an operational Internet connection is available.

## References

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