Foundation monitoring for offshore windfarms

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Summary

The offshore wind energy industry is still relatively young. There is little or simply not really sufficient experience regarding the safety of the wind turbine foundations; the material stress due to wind and waves is still not completely clear. A continuous foundation monitoring including analysis is therefore needed.

Some offshore foundation monitoring projects are initiated in response to the BSH requirement to equip 10% of all offshore structures with a foundation monitoring system. In all cases where calculation results are not fully adequate and do not include sufficient safety margins for the particular aspect, the observation method according to DIN EN 1997-1 (EC-7-1) and DIN 1054 must be applied. Usually, there are additional individual requirements for each offshore wind farm project.

Foundation monitoring concepts include:

- Prognosis of the probable structure behaviour
- Determination of the limits of the allowed structure behaviour
- Definition of a measurement program (sensors, installation, maintenance, data handling, data analysis, documentation of measurement program)
- Definition of corrective measures to ensure the structure stability in case of alarming measurement results
- Demonstration that corrective measures can be implemented in time to ensure structure stability
- Documentation of the execution of the measurement program

1. Introduction

There is not yet a standard concerning the scope of offshore foundation monitoring projects. Realization details depend on wind park project specifics such as foundation type, water depth, soil conditions, etc. Another important issue is whether the proposed monitoring program should fulfil the basic BSH requirements only or whether the park operator would like to have additional structure information vital to park operation (e.g. grout monitoring).

Typically, foundation monitoring includes:

- scour monitoring
- grout monitoring
- inclination monitoring
- load monitoring
- acceleration monitoring
- monitoring of turbine position
- metocean sensors

The paper will deal with a technical concept to cover this problem.

2. BSH Requirements

Most offshore foundation monitoring projects are initiated in response to the BSH requirement to equip 10% of all offshore structures with a foundation monitoring system. Due to the lack of knowledge how cyclic loads will influence the structures offshore, the general requirements specify that a measurement program must be installed. In some projects the observation method specified in DIN 1054 / EC7 may be applied. Usually, there are additional individual requirements of the BSH for each offshore wind farm project. Furthermore, a certified concept detailing the application of the monitoring method must be submitted to the BSH.

These concepts should include (minimum):

- Sensor details and datasheets
- Placement of sensors
- Installation, commissioning and calibration of sensors
- Maintenance plan
- Data handling
- Data analysis
- Documentation of the execution of the measurement program

In case the observation method is being applied, there are additional requirements to be considered in the measurement concept:

- Prognosis of the probable structure behaviour
- Determination of the limits of the allowed structure behaviour
- Definition of corrective measures to ensure the structure stability in case of alarming measurement results
- Demonstration that corrective measures can be implemented in time to ensure structure stability.

3. General Requirements

In all offshore measurement projects, it is important to work closely with the wind park operator on the conceptual details in order to ensure the best possible solution for his individual needs.
Important aspects are

- redundancy and data security
- low maintenance
- easy and fast offshore installation
- SCADA: one interface for the wind park operator

In addition, as all works done offshore are expensive, it is important to do as much installation work as possible onshore. Offshore work should, if possible, be reduced to ‘connecting plugs and switching switches’. The goal is to reduce the time needed offshore and the possibility of making costly errors. All equipment should be run onshore in a test run simulating full operation.

It is important to put a strong focus on determining which data the wind park operator needs in his daily business. These data need to be integrated into his control room software. It shouldn’t be necessary to use several different programs to operate the many different subsystems of one wind farm.

4. Targets

Typical Targets are:

- Corrosion
- Stability of grout connections
- Movement of piles in the soil
- Inclination
- Foundation accelerations
- Foundation loads
- Bolt forces on flange connections
- Poisonous or flammable gas concentrations

Some Targets are difficult to measure directly.

4.1. Corrosion

Corrosion is a locally varying phenomenon. Different kinds of corrosion may occur

- GALVANIC CORROSION
- PITTING CORROSION
- SELECTIVE ATTACK
- STRAY CURRENT CORROSION
- MICROBIAL CORROSION
- INTERGRANULAR CORROSION
- CONCENTRATION CELL CORROSION (CREVICE)
- THERMOGALVANIC CORROSION
- ….

In most projects, only an overall average corrosion rate can be measured. The determination and the detection of a specific corrosion is difficult.

4.2. Grouted connections

The grout connection is typically extended spatially over several meters. There are no reliable measurement principles known. In most projects, the relative movement of the two connected pieces is measured, e.g. movement of transition piece versus monopile. Industry standard distance sensors can be used here. Care has to be taken to ensure the resistance to offshore conditions of the sensors and the measurement principle itself.

For jacket and tripod constructions, the grout connections are under water, in depths of 20 to 50 m. In this case no standard solutions for the measurement of relative movement are available. Research is being done by a variety of companies on the development of a suitable sensor.

4.3. Pile movement

The movement of piles in the soil is very difficult to measure. A special challenge is the measurement of underwater piles of tripod and jacket foundations. In most projects, the foundation inclination is measured instead, which gives indirect evidence about pile movements.(q.v. [1]).In some projects, differential GPS measurement is used in addition.

4.3.1. RTK

The use of geographic coordinates needs a very high precision. The resolution has to be in the range of 10 mm. Real Time Kinematic (RTK) GPS systems provide real time, very high accuracy positioning and tidal information. This system needs a reference station and communication between the measuring points. The measurements take place at regular intervals and after storm events. (q.v. [2])

4.3.2. Inclination

Constantly changing wind and wave conditions cause abrupt load changes in wind turbines. Particularly during strong gusts of wind, storms or a wind energy system's start-up phase, towers can tilt so much that the overall system lifetime can be affected. A key requirement of pile installation is pile verticality. Traditionally, the verticality or inclination has been measured by means of pausing the piling and measure the inclination using handheld inclinometers. Inclination sensors are able to measure deviations relatively to a horizontal axis of rotation in an angular range up to 360°. Deviations have to be determined quickly and precisely. A continuous measurement has to detect an inclination difference of 0.05°. This precision has to be guaranteed for up to 20 years. Most sensors aren't able to deliver this long-term stability. Some sensors used in building monitoring systems are able to deliver these needs. Cyclic loads which cause inclinations of around 0.05° are a special challenge. Those sensors have to be unsusceptible to cyclic loads.

Inclination sensors have to fulfill the following requirements:

- precision better than +-0.01°
- resolution better than +-0.005°
- long-term stability
- high time constant

4.3.3. Acceleration measurement

A wind turbine system is highly nonlinear and its dynamic changes rapidly with the change of wind. The mechanical structure of wind turbines is flexible due to its great height and the structure tends to oscillate. The frequencies vary between 0.1Hz and 10Hz. The sensor has to cope with very low (quasi static) changes. The sampling frequency should be at 50 Hz. (q. v:[3])

4.4. Strain gauges

Strain gauges can be applied in order to detect the loads transferred into the foundation. The interconnection should be done as a temperature-compensated half-bridge, or even better as a full bridge. When selecting the adhesive and cover material the long term stability should be an important criterion. Typically two full bridges as bending measuring points in the x-and y-direction and a full-bridge as a torsion measuring point are used. For strain gauge application, the protective coating of the structure has to be removed in order to apply the sensors on bare metal. The application area is then covered again to protect against environmental influences, as strain gauge applications are extremely sensitive to the intrusion of water.

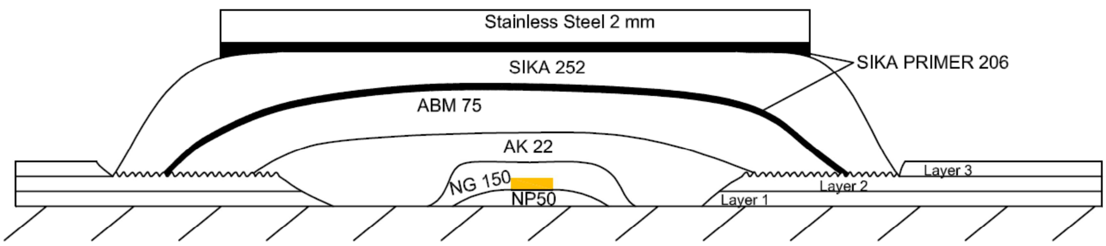

Fig. 1: Application of strain gauges

The picture above provides an example of a typical strain gauge coating. The materials used in this example are: NG 150 (Hottinger Baldwin Messtechnik) / AK22 (Hottinger Baldwin Messtechnik) / ABM 75 (Hottinger Baldwin Messtechnik) / SIKA Primer 206 (SIKA) / SIKA 252 (SIKA) / SIKA Primer 206 (SIKA) / Stainless Steel 2mm

4.5. Bolt force measurement

The bolt force measurement can be done by an ultrasonic measurement system. The main advantage is that there is no bolt modification needed. The alternative is a strain gauge measurement. The main advantage here is the low price, but in order to get the best result the bolts have to be modified. To achieve a considerable cost savings, applying conventional strain gauges to the bolts seems to be possible. The strain gauges are connected to a temperature compensated full bridge measuring bolt forces without sensitivity to bending moments. But for mechanical protection, the bolts should be modified and the strain gauges should be covered with sealing compound and a steel plate. The following sketch provides an impression.

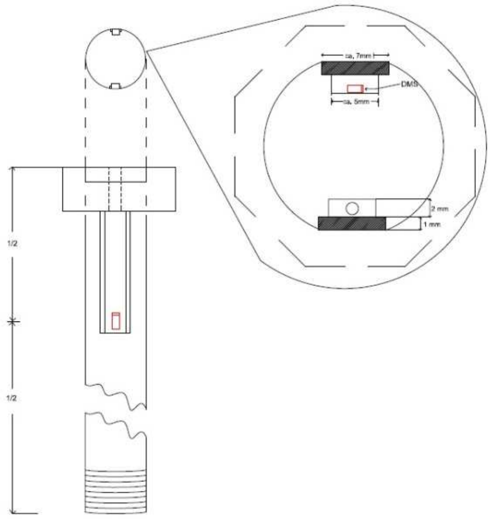

Fig. 2: Modified Bolt

4.6. Scour, Waves and Current

The characteristics of the local and global scour development described by depths and extent are directly influenced by the wave parameters and the orientation, i.e. turning angles of the tripod inreference to the main wave direction. It can generally be concluded that scours occur directly at the piles and also in the near-field and beneath the main column of the tripod, in some cases reaching even higher scour depths than expected around the piles. Therefore, the influence of the global changing bed surface on the soil-mechanical bed characteristics has to be considered when regarding the stability of the soil and the structure itself. [4]

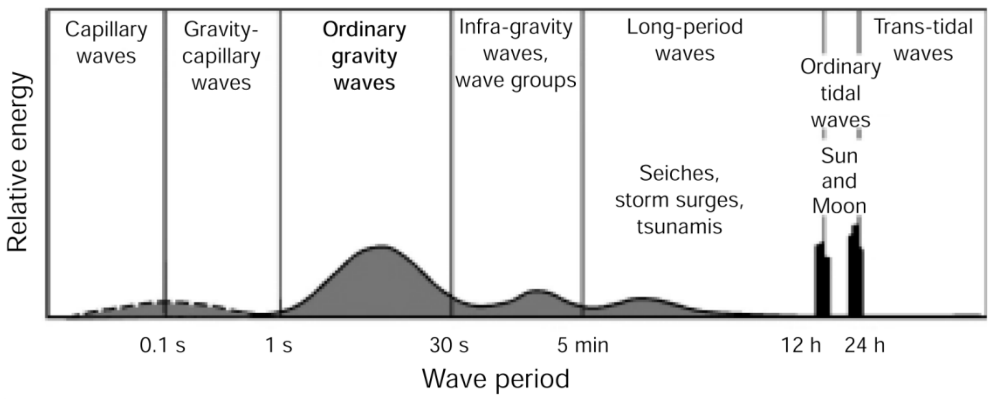

Fig 3: Characterization of waves [5]

Waves and currents influence so many processes and operations at sea; hence many techniques have been invented for measuring waves. Here are two of the more commonly used techniques are shown. Because of the resulting physical effects which may influence the wave measurement, it is important to know how the applied device works.

4.6.1. Current measurements

An acoustic Doppler current profiler or ADP is used to measure how fast water is moving through the whole water column. They can be fixed on the seabed to measure the current across the water. ADPs work by sending out a pulse of sonar and “listening” for a return. This return is generated from particles in the water, if the particles are moving it is subject to Doppler shift. The amount of the

Doppler shift can be used to calculate the speed and direction that the water is moving. This is detailed information about the current for this very location.

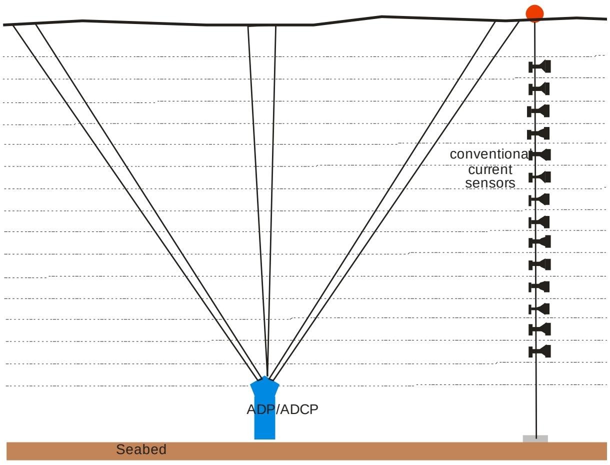

Fig.4: Current measurements

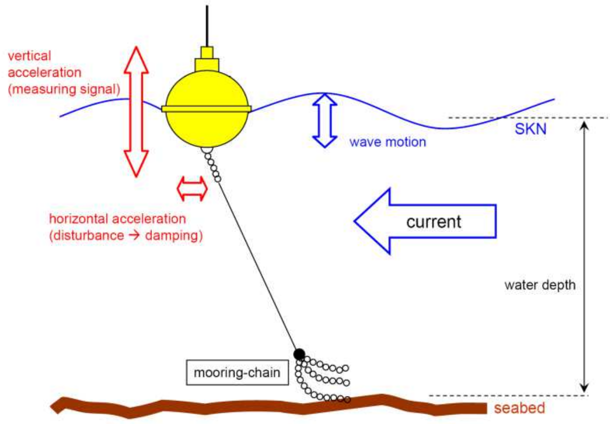

Fig.5: Wave measurements

4.6.2. Wave measurements

Direct measurements with movable devices such as a buoy are affected by unwanted acceleration signals as a result of the movement of the water surface. Buoys provide accurate wave information at a specific location. However, the buoys must be moored and can be lost due to bad weather and collisions by other ships. Measurements of directional waves are often required. In the past, specially designed equipment was often used to provide wave data, which required complex installations and significant costs. Earlier pressure-velocity systems lacked the accuracy especially when to water gets deeper. Recently introduced ADP-based beam systems are reported to be capable. There are some improvements like the AST-Method. The Results of this Acoustic Surface Tracking (AST) are very comparable to the standard method of wave measurements like buoys.Modern Buoys can be equipped with a current sensor. This current sensor works like a normal ADP/ADCP (Acoustic Doppler Current Profiler).

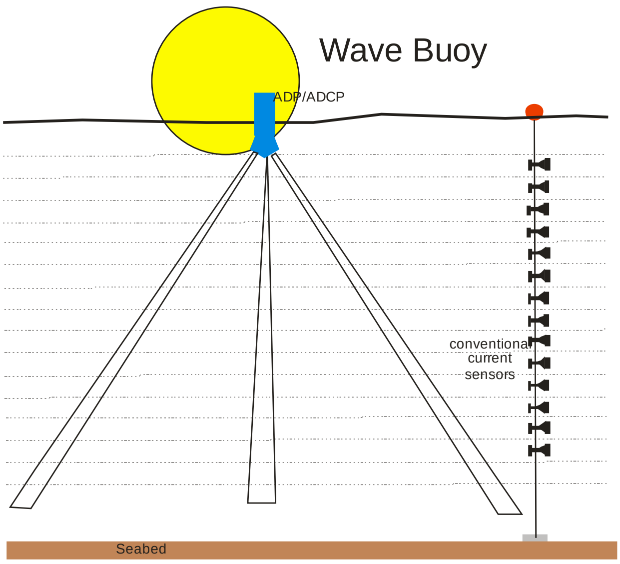

Fig.6: Buoy hull with integrated ADCP/ADP

All the different wave and current measurement devices and techniques do have their pro's and con's especially under different weather conditions. An ADCP with AST is a promising solution to measure both, waves and current. As an all-in-one solution it saves money, it is robust because of no movable parts and very accurate in measuring the direct water elevation. But for its deployment and maintenance divers are often needed. A buoy with currents is also capable to measure the majority of the needed parameters and the maintenance effort is less.

4.6.3. Scour measurement

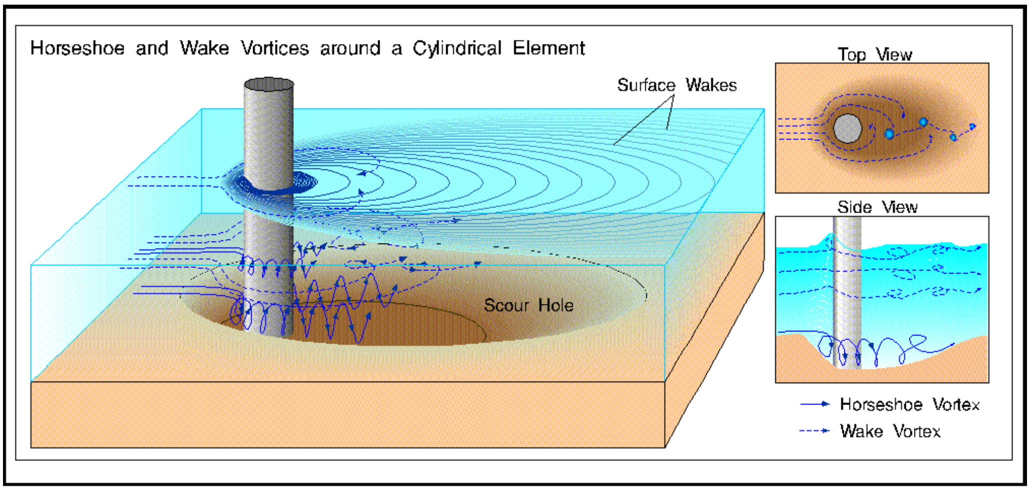

Fig.7: Scour [6]

Scour measurement is a well-known issue on bridge over waterways. Three main systems are used to monitor the scour:

1. Float-out devices
2. Magnetic collars
3. Sonar (ultrasonic devices)

The float out device concept is to bury transmitters at various locations around a structure which would eventually cause them to be released due to the scour's removal of material around the device. A receiver on the structure would receive the transmission and perform an action. A float out device system would provide an initial indication of scour severity for further investigation. [7]

Magnetic sliding collars are rods or masts that are attached to the face of a pier or abutment and driven or augered into the streambed. A collar with magnetic sensorsis placed on the streambed around the rod. If the stream bed erodes, the collar moves or slides down the rod into the scour hole. The depth of the collar provides information on the scour that has occurred at that particular location. [8]

The sonar instrument measures the distance from the sonar head to the riverbed and back based on the travel time of a sound wave through water. Sonar sensors normally take a rapid series of measurements and use an averaging scheme to determine the distance from the sonar transducer to the stream bed. These instruments can track both the scour and refill (deposition) processes.[8]

The newest and most promising product is a multi-beam sonar. An area could be monitored with only one device.

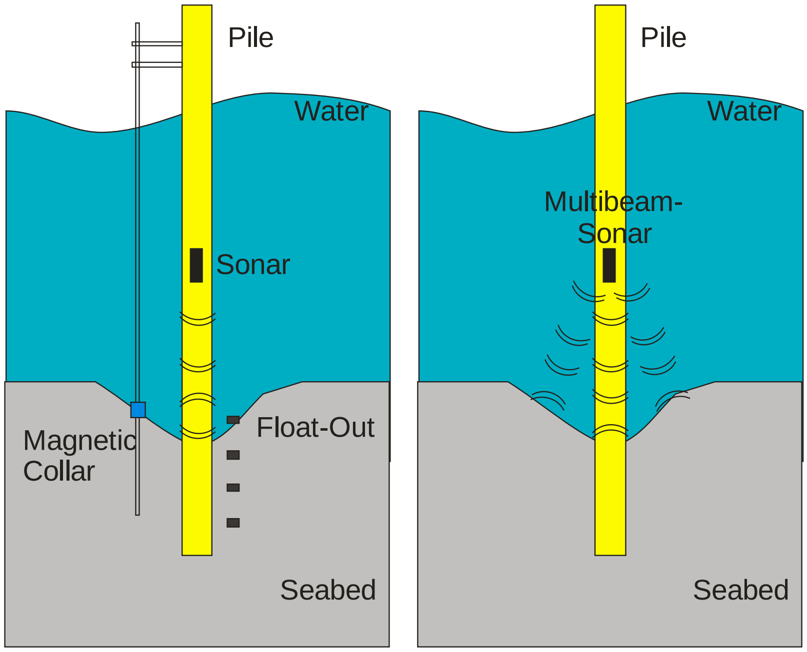

Fig. 8: Scour detection

5. Data Acquisition

The data acquisition system will be distributed over several wind turbines. In each turbine we usually use a programmable measurement system with local hard disk to collect the monitoring data. Communication will be done via TCP/IP. We expect a local Ethernet network with access from mainland to be available.
Measurement equipment like signal conditioner, AD-converter etc. should be an industrial grade scalable system. The requirements known at this time are not very high: sample rate ca. 100Hz, about 40 signals. But scalability is an important issue therefore expandable systems should be used. Typical add-onsare extremely fast channels, additional channels, any kind of sensor/signal conditioning, use of a special digital input frequency filter, online pre-calculation of values, automatic online data evaluation, etc…

The following important features should be taken into account:

- scalability
- an internal bus, so distribution of the equipment inside the turbine is possible
- galvanic isolation of channels
- hot swap (plug and measure) capability
- operation in temperatures from -20°C to +50°C
- excellent EMV characteristics
- a programmable controller on each turbine – online data evaluation possible in later project stages
- an interface to Profibus-DP or Modbus RTU possible

It is not uncommon for most modern computer-based systems to suspend operation for unknown reasons. For all offshore measurement equipment, in order to ensure maximum data availability, it is necessary that the system doesn't "freeze up" after power downs, long periods of elapsed time or any other events. To avoid these situations proven industrial measurement equipment should be used. Additionally, equipping all turbines with one IP switch each allows a remote reset of the measurement equipment from onshore.

5.1. Data storage concept

The need for data storage depends on the bandwidths of the data transfer lines, the service intervals on the wind turbines and on the individual needs of the wind park operator. This should be discussed with the wind park operator prior to submission of a detailed concept.

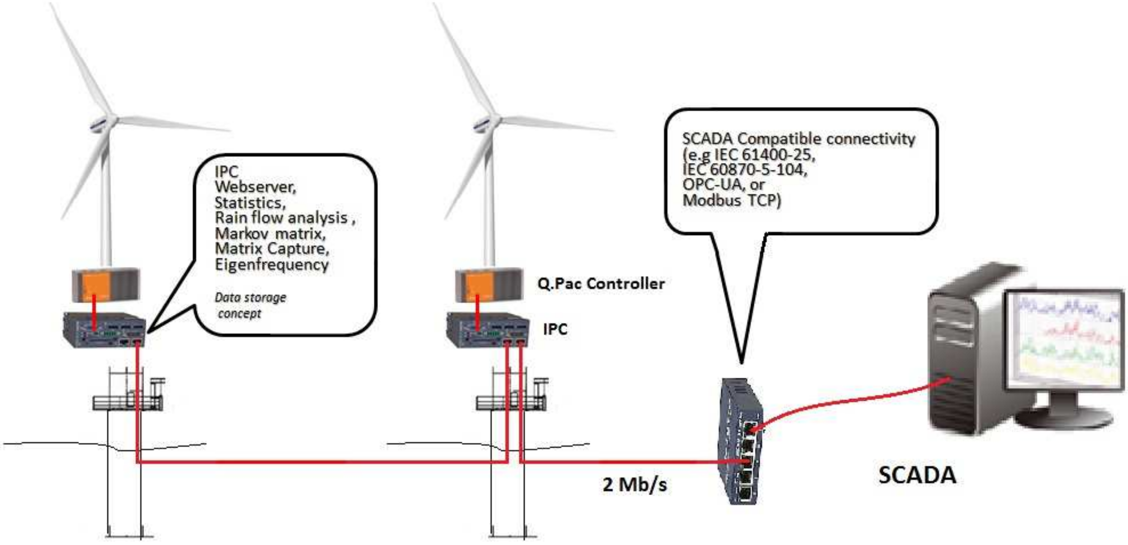

Fig. 9: Data Concept
In most projects data can be transferred on a daily basis to an onshore base for data evaluation. Only small data storage systems on each turbine are provided for temporary data storage.

5.2. SCADA

All equipment is accessible via TCP/IP. ASCII can be selected as the data format and it is then compatible with any SCADA system. In our experience in a multitude of offshore foundation monitoring projects, we expect two aspects to become increasingly important in future projects:

- the connection to a SCADA system of the 24/7 operational base, usually via a standard power industry protocol like IEC60870-5-104, IEC61850, IEC61400-25 or other;
- the automatic online generation of warnings;
- complex evaluation algorithms for the generation of warnings must be executed automatically and online; and
- the integration of turbine control data and of environmental data for data evaluation purposes.

5.3. Data evaluation

A basic data evaluation will be done offshore by the measurement equipment. A daily table will be created with header and statistic data: For an evaluation like this, the measurement values for wind speed and wave height will have to be made available to the measurement system by the wind farm operator. Electric power generation, wind direction, azimuth angle and pitch angle should also be measured to provide a better basis for the data interpretation.For the damage calculation, a rain flow analysis has to be done for the strain values of each measurement level. Subsequently, a ‘markov matrix’ should be generated for each level. The corresponding markov matrices for each layer from the design damage prognosis will have to be provided by the designer. Data evaluation should include data classification according to EN 61400-13. In addition, an alarm database and the introduction of a learning process is very important.

6. References

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