Development and Installation of a Robust and Reliable Research Structural Health Monitoring System for Grouted Joints of Offshore Wind Turbines

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ABSTRACT

Offshore wind turbines are highly exposed to operating loads and extreme environmental conditions. To ensure technically reliable and economically worthwhile operation, high plant availability must be provided. Structural health monitoring (SHM) respectively condition monitoring (CM) makes a valuable contribution to this.

The grout connection used in offshore foundations is usually monitored in compliance with regulatory requirements, e. g. VDI 4551 or insurance conditions.

In the project "In-Situ-WIND" an extended hard, - and software concept adapted to the SHM-application, based on vibration-based methods, acoustic emission analysis and radar measurement technology was developed. The overall objective of the project is to find a suitable system configuration and appropriate methods to monitor the grout connection.

The challenges are that the measurement system needs to operate reliable under extreme environmental conditions in the grout area, must be accessible remotely due to extremely limited accessibility and the offshore installation should be carried out time-efficiently under very difficult installation conditions.

Due to this, a decentralized measurement system has been set up. A central server cabinet in the entrance area of the wind turbine contains the essential components for power supply, data storage and data processing. A redundant, diagnosable, and remotely maintainable design of many of these central components increases the reliability of the overall measuring system. One measurement system is placed directly in the grout area in a rugged offshore-ready control cabinet and receives signals from 50 channels of different sensors. Due to limited installation options, a hybrid cable for power supply and data transmission was used to connect the system with the control cabinet in the entrance area. Another measuring system records the vibrations of the tower by several acceleration sensors.

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The synchronization of all measurement channels, data storage and data processing are performed centralized by the components in the server cabinet. Additional added value is created by integrating another measurement system of the wind farm operator, as well as the SCADA data. Additionally, a further radar measurement system of Goethe University Frankfurt was connected.

Due to the careful and extensive preparation and planning, the complete reliable and robust measurement system has been installed offshore in an extremely time-efficient manner. Due to its forward-looking planning, the system has now been in operation since September 2021, has a very high availability and provides high-quality measurement data.

INTRODUCTION

The foundation structures of offshore wind turbines are exposed to high mechanical loads and extreme environmental conditions. Therefore, this important structural element should not only be robustly designed, but also continuously monitored for any damage [1,2]. Standards applied so far, such as the German guideline VDI 4551, give only vague recommendations regarding the monitoring of grouted joints, such as "For this purpose, continuous frequency and inclination measurements can be made in order to evaluate deviations in frequency and inclination based on a fixed target value." [3]. Beyond that, no details regarding the technical implementation are given. Therefore, the research project "In-Situ-WIND" is focused, among other things, on the development of a comprehensive, robust and reliable monitoring system adapted to this application for research purposes. Comparable installations are described by [4], [5] or [6], for example. In the following, technical aspects of the installation of SHM-Systems in offshore environment will be discussed in particular.

MAIN TARGETS AND REQUIREMENTS

The aim is to develop a reliable SHM-system for grout connections of offshore wind turbines (OWT) with monopile (MP) foundation Different approaches are being pursued. On the one hand, monitoring is to be carried out by means of vibration measurement data. For this purpose, changes in the vibrational behavior of the turbine caused by changes in the grout connection shall be recognized. By means of acoustic emission analysis, transient structure-borne noise events are analyzed and related to the vibration measurement data. The sensors are installed on two levels on the monopile and transition piece (TP) close to the grouted joint in order to enable the investigation of the grouted joint and to avoid other dominating influences. The corresponding surfaces are very corroded and continuously exposed to condensation and a humid-salty atmosphere. Since the grout area is hermetically sealed but subjected to the tidal range, high pressure oscillations occur in this section of the plant [7].

In order to record the overall vibration behavior of the tower and transition piece, which affects the behavior of the grout connection, acceleration sensors are also installed at three levels in the tower.

The grout area, resp. grout connection, is located about 17 meters below the entrance level of the wind turbine and can only be reached via ladders and narrow hatches. Loads must be transported laboriously and carefully by temporary installed rope lifting equipment. Also in the tower, all installation activities have to be carried out from ladders despite the presence of an elevator. All the necessary connections, such as power supply and network connection, are located on site in the entrance area. For safety reasons, cables can only be routed in appropriate cable trays existing on site and must be fed into the grout area through a special cable transit.

Since a plant shutdown and technician deployments result in high losses of profit and costs for staff and logistics in particular, an installation of measurement equipment at an offshore wind turbine must be carried out in an extremely time-efficient manner.

Due to extremely limited accessibility, the central components of the overall system must be designed redundantly and be remotely diagnosable and rebootable to ensure reliability. Due to this, the failure of individual components, be it measurement technology or voltage supply, will not lead to a total failure.

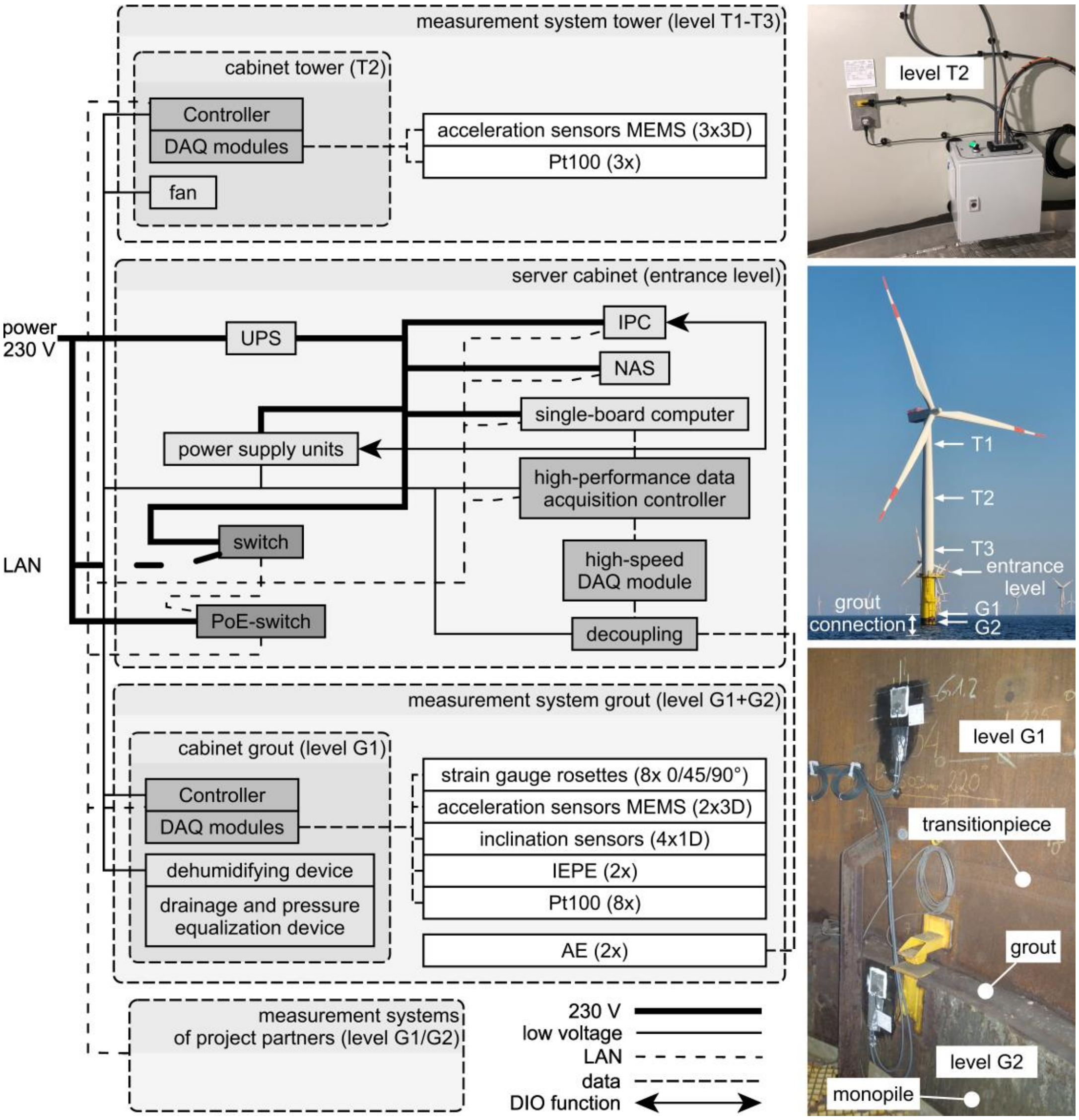

Figure 1. Main elements of the measurement system (left) and installation levels in the offshore wind turbine (right).

HARDWARE AND INSTALLATION CONCEPT OF THE MEASUREMENT SYSTEM

In order to meet the on-site conditions and to make the installation as time and cost efficient as possible, a decentralized measurement system configuration is used, as schematically shown in Figure 1. A detailed description of the components is given in the next sections.

Grout area and tower each form a measuring area and are covered by a locally installed measuring system (see Figure 2). The connection between the measurement systems is made by means of a central server cabinet at the entrance level of the wind turbine. A major advantage of this decentralized configuration is, that each system, which can also be operated individually in principle, can be optimized w.r.t. to its respective location. For example, only the grout measuring system has to be “especially” protected with a robust housing in accordance with the extreme environmental conditions existing there, whereas other sub-systems in the tower or transition piece can be installed in "normal" cabinets. Another major advantage is the possibility to connect the grout measuring system with only one hybrid cable for power supply and network connection. This minimizes the installation effort for cable routing considerable.

In contrast, commercial installations often use a central measurement system located in the entrance area, which means that a correspondingly long cable must also be routed for each sensor at great expense [8,6]. Furthermore, each cable has to be routed through an airtight cable transit into the grout area, which requires a high installation effort. The cable lengths in the described decentralized system are minimally short in total.

As already indicated, the time required for the offshore installation itself is a cost factor that should not be underestimated. Therefore, great importance was attached to optimized time, task and personnel planning, logistics and preparation within the framework of the research project "In-Situ-WIND". Thus, the entire measuring system and also the entire procedure associated with the installation were planned down to the smallest detail. The measurement system was set up, configured, electrically approved and intensively tested in the laboratory before the offshore installation. The packaging and logistics were planned and executed in such a way that finally a fast and demand-oriented transport inside the offshore wind turbine could take place.

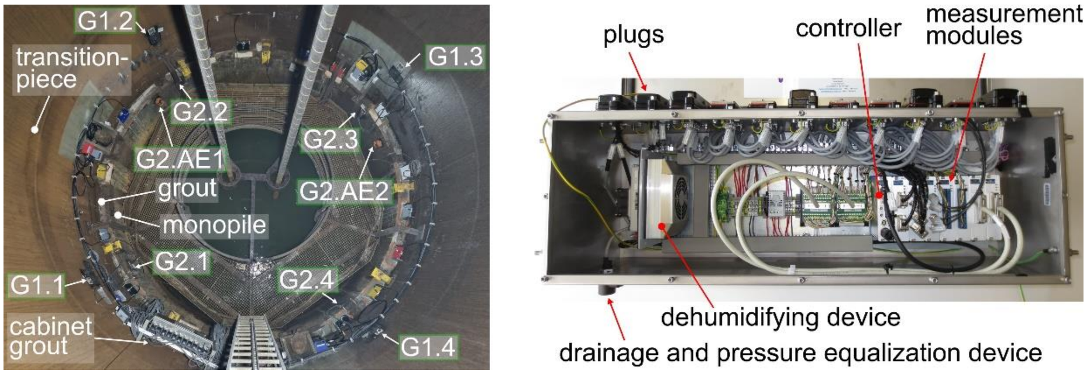

Figure 2. Measurement system and sensor positions in the grout area (left); grout control cabinet with measuring system and dehumidification equipment (right).

Pre-assembled IP68-certified modular connectors enable plug-and-play installation even offshore in the grout area. Apart from a few exceptions, all sensors of a measuring position in the grout area were connected to one common connector. The strain gauges have also already been assembled in the laboratory. Hence, no soldering work was necessary on site. Prepared mounting brackets with glued-in magnets enable quick, easy and accurate mounting of all sensors that can be screwed on. Cable trays could be set up quickly and properly using magnetic holders.

Due to the remote accessibility of the system components via the network, released by the wind farm operator, the systems could already be started and tested remotely by other colleagues from onshore during the running offshore installation.

SYSTEM COMPONENTS

Central Server Cabinet

The central server cabinet is placed in the entrance area of the wind turbine. In addition to minimize the transport effort, it was of advantage that the necessary supply infrastructure consisting of power and network connection is available here as well. The server cabinet contains all the central components of the measuring system, which are required for the power supply, data linking and data storage of the overall system.

The centerpiece of the measuring system is a high-performance data acquisition controller. This synchronizes and bundles the data streams of the three installed (sub-) measurement systems with 64 channels in total and stores the recorded measurement data on a NAS (Network Attached Storage), which is also housed in the control cabinet. Due to the high data transfer rates, the acoustic emission measurement system was connected to the high-performance data acquisition controller via an USB cable that is as short as possible. The NAS is also accessed by an IPC (Industrial Personal Computer) installed in the same control cabinet. This handles parts of the data pre-processing, i.e. files are summarized, filtered and converted into a standardized data format. In order to pre-process the data and to extract simple features, some algorithms run on the IPC as well. Through digital input/output (DIO) the IPC is also able to monitor the functionality of the installed redundant DC power supplies and fuse modules and to reset tripped fuses if necessary. Furthermore, the DIO's can be used to perform restarts of all measuring systems via contactor. An uninterruptible power supply (UPS) is used to shut down all systems, especially the IPC and the NAS, in a controlled manner in case of a power failure.

Grout Measurement System

The grout measurement system records 50 measurement channels. These include strain gauges, acceleration, inclination, acoustic emission and temperature sensors. The measurement system itself is installed in a self-designed, IP68-certified stainless steel control cabinet and is composed of a controller and seven measurement modules, as shown in Figure 2. The control cabinet is suspended from a ceiling eyelet in the grout area and positioned with magnets on the inner wall of the transition piece. In order to be able to remove any humidity and condensation that may be present inside the cabinet, a humidity-controlled dehumidifier is installed, which removes the water via a drain valve. A pressure compensation valve is used to equalize the pressure inside the control cabinet with the ambient pressure in the grout area, which fluctuates due to the tidal variation [7]. The control cabinet is connected to the server cabinet in the entrance area via a hybrid cable, which provides the 24 VDC power supply and the network connection at the same time.

Figure 2 also shows the extensive installations in the grout area. There, sensors of the University of Siegen are installed in two levels, 100-250 mm below the grout surface at the monopile and 1100-1300 mm above it at the transition piece. These are installed at four positions with 90° offset to each other over the circumference. Thus, there are eight measuring points for vibration monitoring in the grout area.

A strain gauge rosette with three measuring grids in 0°/45°/90° arrangement is applied at each of the eight positions, so that a complete measurement of the local stress state and the calculation of the changes of the stress resultants in the area of the transition piece according to [9,3] is possible. For computational temperature compensation of the strain values, Pt100 temperature sensors are mounted in the immediate surroundings of each strain gauge. The strain gauges and temperature sensors are connected via offshore-suitable, double-shielded measuring cables in 3-wire technology and quarter-bridge circuit resp. 4-wire technology. The installation process of the strain gauges is shown in Figure 3 was done by Fraunhofer LBF. First, the relatively thick corrosion layer was sanded down to bare steel and temporarily protected against flash rust with a primer. Using a powerful halogen spotlight, the installation surface was warmed up on the following installation day so that no humidity could condense on this surface during the following application of the strain gauge. The primer was removed locally at the actual measuring positions, and the strain gauges were applied to the surface, which had again been carefully sanded, in accordance with the usual procedure. The measuring points have been protected against humidity penetration by a kneadable putty with aluminum foil and additionally sealed at the edges and cable entrances with a two-component adhesive.

Triaxial accelerometers are installed on both, the monopile and the transition piece. These are offshore-certified MEMS sensors with high sensitivity (2000 mV/g), very low spectral noise (7 μg/√Hz) and a measurement range of ±2g. The sensors are screwed onto mounting plates, which are attached to the wall of the transition piece and monopile by magnets and glued with additional structural adhesive.

The inclination sensors are also MEMS sensors, but with only one measuring channel per sensor and a measuring range of ±10°. These also have a high sensitivity (475 mV/deg) and accuracy (< 0,05°). Two sensors are installed at 90° to each other on both measuring planes, so that a tilt resultant to the vertical can also be determined here.

Figure 3. Installation steps of a strain gauge and a Pt100 temperature sensor done by Fraunhofer LBF.

The selected sensor arrangement of acceleration and inclination sensors makes it possible to describe the movement or orientation of the transition piece and the monopile. A difference analysis can also be useful to evaluate relative movements between the monopile and transition piece.

A piezo acceleration sensor and a pressure sensor are also installed on mounting brackets on the monopile to measure vibrations in the audible frequency range. In particular, these can also be used to detect or classify external events, such as pushing events of the crew transport vessel (CTV). Two acoustic emission sensors have also been installed to cover the frequency range from approx. 80 to 500 kHz.

Tower Measurement System

The tower measurement system is composed of three triaxial MEMS accelerometers and three (plus one in cabinet) Pt100 temperature sensors. The sensors are installed on three levels in the tower (T1 to T3) of the wind turbine according to Figure 1 and connected to a measurement system installed on the middle level (T2). This consists of another controller and three measurement modules. In contrast to the grout area, the environmental conditions in the tower are very good except the possible stronger vibrations. Only the accessibility to the sensor positions and cable routes over ladders is difficult. In this case, the controller can be connected to the high-performance data acquisition controller cost-effectively via a control cable for the power supply and a separate ethernet cable.

EXTENSIONS

Since the capacities of data storage and data evaluation are limited offshore, the raw data and the features collected offshore are copied resp. mirrored via a VPN tunnel to data servers of the University of Siegen and the Goethe University Frankfurt. The data processing is carried out by further computers and also high-performance computing clusters.

Additional added value is created by retrieving the SCADA data of the wind turbine via the protocol IEC 60870-5-104 using the software “OpenMUC” and storing it with the measurement data [10]. Thus, a data evaluation under consideration or compensation of the environmental influences is possible. Furthermore, the measurement data of another measurement system of the wind farm operator are also retrieved via FTP, so that other sensor types and measurement positions can also be taken into account in the data evaluation.

The connection of further measuring systems of research partners is also carried out via the network switches installed in the server cabinet.

Using a method synthesis, the advantages of the more global vibration measurement technology are to be combined with the advantages of the locally acting radar measurement technology of the research partner Goethe University Frankfurt [7].

Parallel to the offshore measurement, experiments are also done on a laboratory demonstrator in order to be able to develop the corresponding algorithms in a target-oriented manner.

SUMMARY

This paper describes the instrumentation of an offshore wind turbine with measurement equipment for research purposes. Compared to typical commercial solutions, a concept optimized for the installation and operating conditions is proposed here, which also ensures very reliable operation due to its very high redundancy and remote maintainability. Added value can be achieved by integrating measurement data from other measurement systems and the SCADA system. Thanks to forward-looking planning and preparation, the extensive offshore installation of the vibration-based measurement system of the University of Siegen was completed in just five days.

Based on these high-quality measurement data, the findings from experiments on a laboratory demonstrator and a method synthesis with radar measurements, a reliable and high-quality SHM overall concept for monitoring grout connections will be developed in the following. Based on this, a proposal for a reduced standard SHM concept for monitoring grout joints shall be made.

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