

Development and Implementation of a Combined SHM/CM System to Identify Yield Losses of a 2.4MW Wind Turbine

Marcel Wiemann, Lukas Bonekemper, Benedikt Wüllner, Herbert Friedmann, Peter Kraemer

Abstract. Monitoring of wind turbine critical components has become both obligatory and, in some cases, legally mandated. Due to this, Original Equipment Manufacturers (OEMs) and suppliers have developed and industrialized an extensive portfolio of monitoring systems in recent years. Despite these successful implementations of the before mentioned monitoring concepts, e.g. for ice detection, there remains a need for research and innovative approaches to comprehensively safeguard all critical areas of a wind turbine against damage and suboptimal operation. This paper describes the development and commissioning of an extensive, combined Structural Health Monitoring (SHM) and Condition Monitoring (CM) system for research purposes on a 2.4 MW wind turbine. The resulting measurement data are used primarily to quantify yield losses caused by undesired structural vibrations of rotor blades, the hub, the drivetrain and the nacelle, rather than for damage diagnosis. The already extensively instrumented wind turbine was further equipped with numerous sensor systems. These include telemetry systems for capturing rotational and bending moments of the drivetrain, eddy current sensors for determining the rotor shaft orbit, accelerometers for identifying structural vibrations in supporting structures and rotor blades and meteorological measurement systems for assessing performance-relevant environmental parameters. Additionally, an interface with the turbines control system was established, enabling the synchronous storage and analysis of various operational parameters alongside measurement data. A high-performance 5G connection facilitates the continuous, automated transmission of measurement data and online diagnostics of the connected systems, which are equipped with fail-safe features for self-recovery. The instrumentation was implemented as part of the research project WEA-produktiv, whose long-term objective is to identify yield losses without requiring additional sensor technology. This extensive instrumentation is essential for the deep understanding and identification of significant correlations between measured wind turbine parameters and their impact on

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electricity production.

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1 INTRODUCTION

CM and SHM systems for wind turbines are in most cases mandatory, either due to legal requirements or insurance regulations. These systems cover a broad range of technical components to ensure the safest possible operation. Typical examples include the continuous monitoring of nacelle vibrations, detecting icing or structural damage in rotor blades [1], and the observation of vibration amplitudes in drivetrain components. This paper presents the development, installation, and commissioning of a SHM/CM system on a 2.4 MW Nordex N117 wind turbine that is already extensively instrumented [2]. While far too complex and expensive for serial application, the system provides valuable insights within the research project WEA-produktiv [3, 4]. The overarching goal of the project is to identify power losses without the use of additional sensor technology, relying solely on SCADA data. However, the elaborate instrumentation described here is initially necessary to establish a meaningful understanding of the relationship between the measured vibration data, SCADA parameters, and power production. The recorded measurement data thus primarily serves to identify yield losses caused by undesired structural vibrations originating, for example, from rotor blades, the hub, the drivetrain or the nacelle. In this context, the instrumented system also serves as a so-called fleet leader. In addition to the intensively instrumented plant, the SCADA data of eight other plants are available, which are then to be analyzed with the findings of the fleet leader as part of the population monitoring. This work is complemented by two further publications focusing on data analysis and turbine simulation in Bladed [5, 6]. The following sections describe the instrumentation process from planning to implementation, addressing the requirements of the measurement system, specific challenges and risks, the integration with the turbine interface, and a detailed analysis of the technical components [7]. It is worth noting in this context that, under the terms of a usage agreement, the turbine will remain available to the MSHM working group as a research platform beyond the scope of the current project, meaning that its comprehensive instrumentation will continue to offer significant potential for future research topics and focal areas [8].

2 REQUIREMENT FOR EXTENSIVE INSTRUMENTATION

As outlined in the introduction, the primary purpose of the system is the detection of turbine states that lead to reduced energy yield. In order to identify the aforementioned correlations, the already extensive instrumentation must be further expanded [2]. For instance, essential SCADA parameters related to power generation—such as reactive power, voltage, and current—are currently missing, as are simple timers and counters that would enable quantification of operational states. Furthermore, analysis of historical vibration data has revealed that the installed measurement systems do not record data in a time-synchronized manner, which significantly hinders the ability to correlate events such as blade vibrations with the power production. Likewise, rotor-induced vibrations in drivetrain components cannot be adequately captured. Key environmental parameters—such as those required to determine air density, wind speed, and wind direction—are accessible only via the turbine’s SCADA system and are either sampled at insufficient rates or entirely unavailable for the intended application. These limitations necessitate the establishment of a dedicated turbine interface to capture additional SCADA parameters, implement centralized time synchronization for current and future systems, measure torque and bending moments in drivetrain components, and deploy both a custom environmental monitoring system and a dedicated data transmission solution (via 5G connection).

3 CHALLENGES AND SPECIFIC RISKS FOR THE MEASUREMENT TECHNOLOGY AND PERIPHERALS

The instrumentation requirements directly inform the specifications for the measurement system. The system must be capable of capturing and processing a wide range of sensor data.

Peripheral Requirements

- High-performance 5G connectivity for data transmission and remote access
- Implementation of fail-safe functionalities
 - Self-recovering components and software
- Establishment of a connection to the turbine control system
- Common time base (master clock) for all subsystems

Measurement Technology Requirements

- Torque measurements (generator shaft, rotor shaft)
- Bending moment measurements (rotor shaft)
- Structural vibrations (accelerations and inclinations)
- Temperature monitoring
- Meteorological data (for determining air density, wind direction, and wind speed)
 - Essential for calculating the theoretically achievable power
- Position tracking (rotor shaft, blade positions)

Due to the complexity of the planned system and its integration into a fully operational wind turbine, specific challenges and risks arise that significantly complicate the implementation of the instrumentation and may lead to various complications.

Challenges and Risks

- Extremely limited installation space (existing option platform is fully occupied)
 - Hardly any space available for sensors or the central measurement cabinet
- Antennas on the turbine roof are exposed to wind, weather, and intense vibrations
- External components must be secured with appropriate lightning protection measures
- The existing turbine interface (OPC-XML-DA) is outdated
- Extensive approval processes (to rule out any risk to turbine operation)
- Torque measurement on a fast-rotating generator shaft (1500 RPM)
- Long-term power supply for the rotor shaft telemetry system

4 INSTALLED MEASUREMENT SYSTEM

The following chapter describes the implemented instrumentation, based on relevant subsystems and components, as well as the setbacks and problems during operation and instrumentation. Finally, the planned system expansion is discussed.

4.1 Interface to the SCADA-Server

To achieve the long-term project objective — detecting yield losses without the use of additional sensor systems — it is essential to establish a connection to the turbine's system interface. The parameters currently available or already being recorded are limited to basic environmental data, which are captured and stored via a Modbus system by the project partner Wölfel. Accessing the turbine's SCADA server through the OPC-XML-DA interface enables the acquisition of over 300 parameters from the wind turbine (See Figure 1). These include a wide range of variables from various subsystems (e.g., condition monitoring system (CMS), PITCH, YAW, etc.) as well as key performance indicators such as active power, reactive power, current, voltage, and power limitations. Additionally, the access to internal timers and counters is possible, allowing for availability assessments since commissioning and, consequently, continuous monitoring of turbine performance. Since the planned IT infrastructure includes a dedicated 5G connection, it must be ensured that this poses no threat to the network of the turbine operator or the OEM. Infiltration of the University of Siegen's network must not lead to any security risk for the turbine's operational network. For this reason, a firewall specifically configured by the OEM was implemented to minimize this risk.

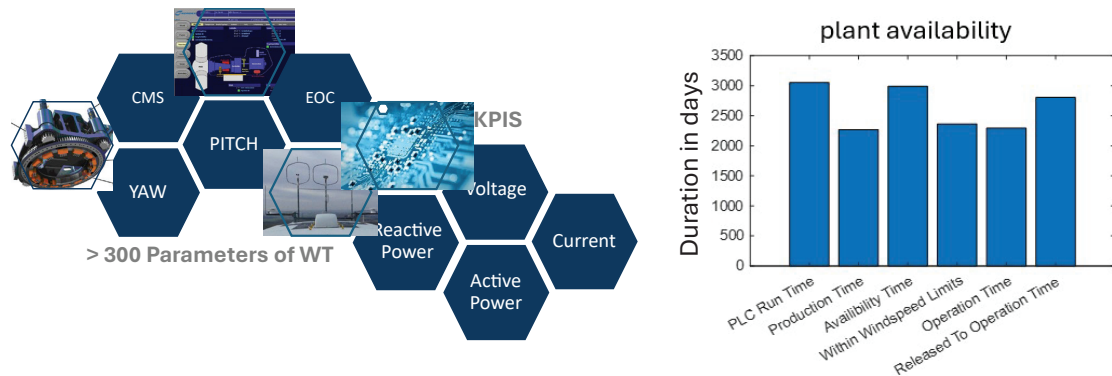


Figure 1: Overview of the possibilities of the OPC-XML-DA interface

4.2 System overview incl. data transmission

The diagram in Figure 2 provides a simplified overview of the planned and partially implemented measurement system, including its peripheral components and infrastructure. Even at the conceptual level, the complexity of the intended installation becomes apparent. Central key components include the IPC, the 5G router, and the time server provided by Hopf Elektronik GmbH. Time synchronization is addressed in detail in a separate chapter. The IPC (industrial computer) is a ruggedized version certified for use in vehicles, making it suitable for withstanding the vibrations typically encountered in wind turbines. It serves as the central hub for collecting measurement data, which is recorded by the Gantner measurement system, the edge base, and the turbine interface. Contrary to earlier concepts [6], no data pre-processing is performed on the IPC. Instead, the collected measurement data is automatically transferred via RSync to a workstation within the University Siegen network, where it is processed and analyzed. Therefore, the reliability of the 5G connection is of critical importance. However, short-term interruptions in connectivity do not pose a significant issue, as the IPC is equipped with sufficient buffer storage.

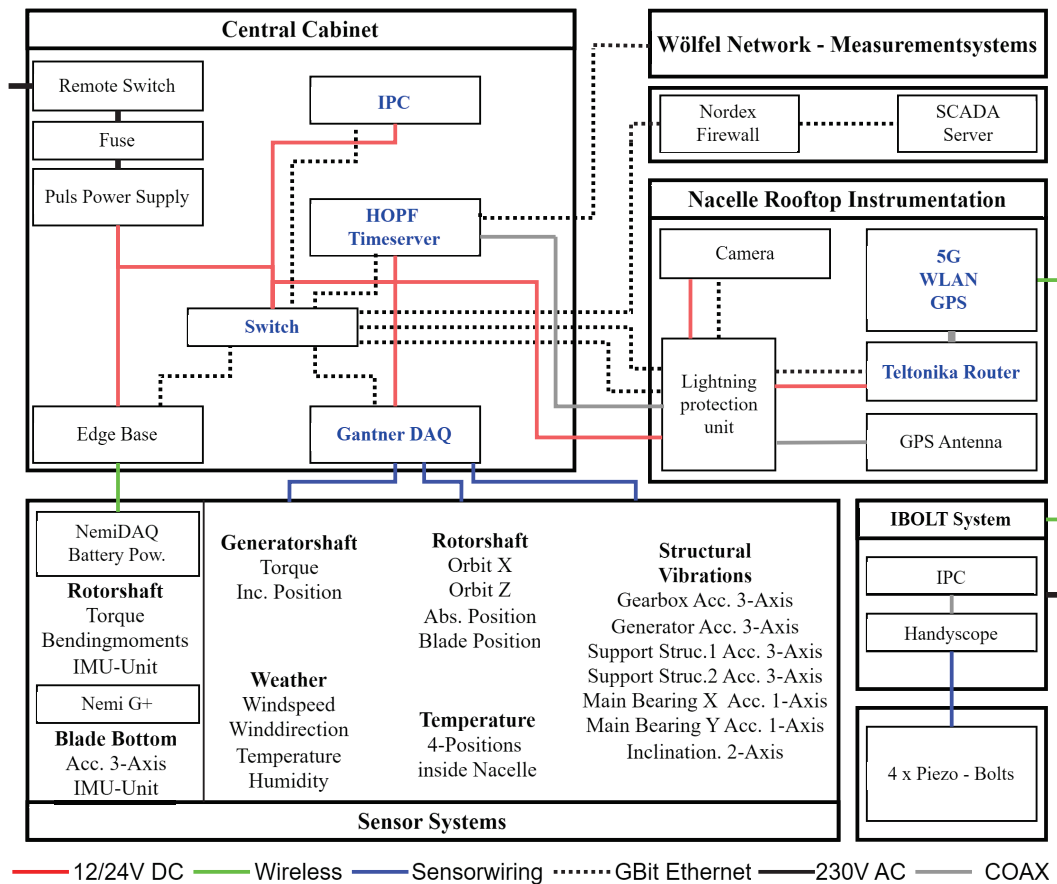


Figure 2: Overview of the implemented instrumentation

4.3 Measuring system – central control cabinet

A large part of the installed sensor system is connected to a central measurement system provided by Gantner. This system consists of a high-performance data acquisition controller and sensor-specific measurement cards. Its modular card-based architecture enables precise tailoring of the system to the instrumentation task at hand. In addition, the central control cabinet houses the evaluation unit for the generator shaft telemetry, power supply, protection systems, the time server, and the IPC. Due to the limited space available, a custom mounting structure had to be designed and integrated into the wind turbine to ensure secure installation of a cabinet of this size. Because of the heat generated by the components, forced ventilation is employed and the cabinet temperature is continuously monitored. The cabinet also provides both network connectivity and power supply for all components. To ensure long-term system availability during extended measurement campaigns, additional safety measures have been implemented. Specifically, it is possible to independently disconnect and restore the power to

system components via two separate subsystems. This functionality allows all components to be recovered from unintended or unforeseen failure states, if necessary. The cabinet weighs approximately 120 kg, which necessitated the use of the turbine's onboard crane for installation.

4.4 Time synchronization via HOPF GPS System

A critical aspect of the implemented instrumentation is the time synchronization of the connected and distributed systems. The system overview shown in Figure 2 represents only a small subset of the measurement systems installed on the turbine. Analysis of historical data has revealed that the recorded measurement data from the various systems are not time-synchronized.



Figure 3: HOPF Timeserver

In the case of simple standalone systems, this issue is usually negligible, as the controllers internal clock is authoritative. However, if data from multiple distributed systems are to be evaluated in a shared context, an appropriate synchronization strategy becomes essential. The installed time server, HOPF 8030 NTS, enables synchronization of a wide range of components (See Figure 3). Synchronization can be performed across two separate networks using the Network Time Protocol (NTP) or the Precision Time Protocol (PTP), or via the hardware-based IRIG-B interface [9]. The achievable accuracies

with PTP or IRIG-B are of the order of 50 ns, which allows for advanced signal processing and system identification techniques—such as operational modal analysis—to be applied across different measurement systems. The internal clock of the time server is synchronized via a high-precision GPS signal, which is received by an antenna mounted on the turbine roof. In theory, this also enables highly accurate synchronization across multiple turbines, which could be particularly valuable in the context of population monitoring—for instance, in studies of wake effects [10].

4.5 Sensorics of the roof of the nacelle



Figure 4: Overview of the roof installation - environmental measurement and antenna setup

Despite the challenges associated with external installations on the nacelle roof of a wind turbine, such an installation was indispensable for this project. With a hub height of 141 meters, the system is subject to an increased risk of lightning strikes as well as continuous exposure to strong wind and precipitation. This results in specific requirements regarding the sealing of components and the implementation of appropriate lightning protection measures. The external installation includes a weather station (for measuring wind speed, wind direction, humidity and temperature), antenna systems (5G router, Wi-Fi, 5G antenna), a camera and a dedicated GPS antenna for time synchronization, see Figure 4. To ensure a high-performance and robust 5G connection to the outside world, the decision was made to place both the 5G router and antenna on the roof. This minimizes cable attenuation between the antenna and router, due to the reduced length of the cable. The systems were mechanically mounted on the turbine's instrumentation tube traverse and electrically grounded with great care to ensure safe discharge of electrical surges. All incoming and outgoing connections are equipped with surge protection to safeguard the components located inside the nacelle.

4.6 Sensorics for structural vibrations

The measurement of structural vibrations is a key component of the overall monitoring system, as the influence of undesired oscillations originating from the nacelle, hub, or rotor blades on power production is to be investigated. Therefore, four triaxial MEMS accelerometers have been installed on the generator, the gearbox and their respective support structures, see e.g. Figure 5. Two uniaxial MEMS accelerometers are mounted on the main bearing. In

addition, tower inclination is continuously monitored using a biaxial tilt sensor. A wireless triaxial MEMS accelerometer with an integrated IMU unit is mounted at the blade root of one of the rotor blades. Additional accelerometers provided by the project partner, as well as sensors that are part of the turbine's built-in IDD.Blade and SHM.Blade systems of Wölfel, supply valuable data from all rotor blades [11], [12]. Together, these data sources enable a comprehensive global analysis of structural vibrations.

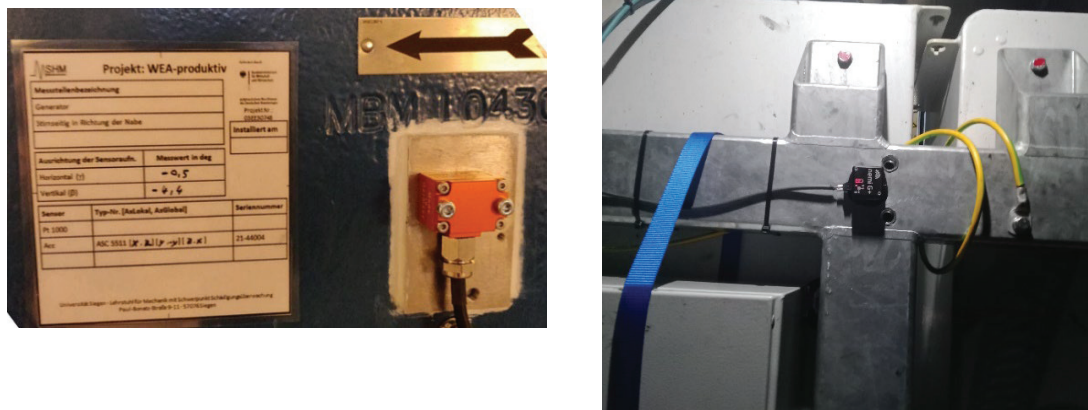


Figure 5: Wired MEMS sensor (left), wireless MEMS sensor (I4M) with attached power supply (right)

4.7 Monitoring of bolted connections

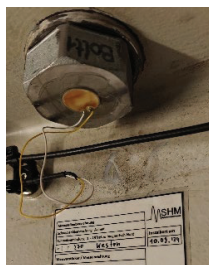


Figure 6:
Instrumented screw head

In addition to the project-specific drivetrain instrumentation and the sensor system for structural health monitoring, a system for monitoring bolt preload beneath the azimuth bearing was installed (see Figure 2, bottom right). This system consists of a dedicated IPC for data preprocessing and control of the measurement device (type: Handyscope). Using a custom-developed multiplexer, measurements are performed on four M36x290 bolts to enable continuous monitoring of the preload force. For this purpose, four standard bolts were replaced with instrumented versions and wired accordingly (see Figure 6). The measurement is carried out via a piezoelectric element applied to the bolt head, enabling precise tracking of preload variations over time [13].

4.8 Sensorics for rotor shaft and generator shaft



Figure 7: Instrumented rotor shaft



Figure 8: Combination sensor holder

To gain detailed insight into rotor-induced vibrations acting on the drivetrain, the rotor shaft was instrumented with a telemetry system from I4M [14], see Figure 7. The telemetry unit is a low-power device approximately the size of a 2.5-inch hard drive, capable of interfacing with three full-bridge strain gauges and evaluating internal IMU data. The collected data is transmitted wirelessly to the Edge Base, where it becomes available for further processing. In addition to torque, the system also records the bending moments of the rotor shaft. Power supply is provided by custom-built battery packs, which are mounted adjacent to the rotor shaft's encoder ring. At a sampling rate of 125 Hz, this setup allows for a measurement duration of approximately 6–7 months. Beyond the measurement of bending and torsional moments, the rotor shaft orbit is also captured. For this purpose, two eddy current sensors are installed with a 90° offset relative to each other, continuously measuring the distance to the rotor shaft with a precision of 0.01 mm. Combined with proximity switches that scan the encoder ring and a reset function triggered by magnets (visible on the right side in Figure 7), which also detect the passage of the blade relative to the tower, the shaft orbit can be referenced to the shaft's absolute position. To ensure precise measurement, the sensors are mounted in a custom-built, solid sensor bracket bolted beneath the rotor shaft (Figure 8). For reliable long-term monitoring,

it is essential to guarantee that no changes occur to the sensor setup. Therefore, all position-sensitive components are marked with tamper-evident sealant. Any minor change or loosening of nuts or bolts would thus become clearly visible during inspection.

4.9 Setbacks of the installation – lessons learned

Due to the complexity of the system and the implementation of novel technologies by MSHM / University of Siegen, various setbacks and issues were anticipated. The most critical of these are briefly outlined and explained below:

- **5G Router and Connection Stability**

A key element for the success of the project is the continuous data transfer, realized via a 5G router. To ensure a reliable and stable connection, the router and its antenna were mounted on the nacelle roof. However, an unforeseen complication arose from unexpectedly high vibration amplitudes at the instrumentation support structure. These vibrations caused contact bounce at the SIM card interface, leading to frequent connection losses — particularly during high wind conditions. This issue was resolved by applying a non-conductive grease to the SIM card contacts (to dampen contact bounce) and increasing the contact pressure.

- **Telemetry Unit on the Generator Shaft**

The telemetry unit from Manner, manufactured in 2000 and mounted on the generator shaft, functioned reliably during laboratory testing. However, on the actual turbine fluctuating temperatures and the system's sensitivity to precise air-gap alignment resulted in only short-term reliable measurements. The root cause was identified as aged electrical components—primarily electrolytic capacitors—which impaired the reliability and electromagnetic robustness of the electronics.

- **Measurement System Configuration and Overload Errors**

The specific configuration of the measurement setup—including data storage on the IPC, use of an external synchronization source, conversion of measurement data into MATLAB format, integration of wireless sensors, faulty firmware, and continuous recording from over 30 channels (partly at high sampling rates)—led to sporadic overload errors in the central measurement unit. Due to the uniqueness and complexity of the system configuration, identifying the root cause of the issue proved time-consuming, even with support of the manufacturer.

- **Delays in OEM Approval**

On the organizational side, the planning and approval of the intended instrumentation by the wind turbine OEM took significantly longer than originally anticipated. It is therefore strongly recommended that this aspect be given high priority in future project timelines. One of the main reasons for the delay was the extensive coordination required regarding lightning protection measures.

4.10 Planned system expansion

As part of the planned follow-up project IROs currently in the application stage, the instrumentation is also to be adapted or extended due to extended project objectives. The expansion of the measurement technology results on the one hand from the research priorities of the follow-up project and on the other hand from the experiences of the WEA-produktiv project. An important focus will be the expansion of the sensor technology in the rotor blades of the turbine, where a system from the company I4M will be used to record local strains and inclinations of the rotor blade during rotation. The data is transmitted wirelessly to the edge base and synchronized with the other measurement data using the common time stamp. In addition, the telemetry system on the generator shaft is to be replaced by a wireless system from I4M. The power supply for the components on the rotor shaft and in future also on the generator shaft is to be converted to a solar solution to ensure permanent battery-independent operation. This effort is not only justified by the project-related objectives, but also due to the long-term planned cooperation with the Wölfel company and the existing research contract with Bürger-Energie Altertheim eG, the operator of the wind turbine.

5 CONCLUSIONS

The instrumentation of the wind turbine described in this paper primarily aims to establish correlations between yield losses and vibration phenomena. As a basis for the overarching objective of identifying yield losses without additional sensors, using only SCADA data. Due to the complexity of the planned and implemented instrumentation, the installation, commissioning and continuous operation was and is a challenge, but in retrospect, apart from the setbacks mentioned, it was a great success. The documentation requirements, ensuring safe plant operation, i.e. ruling out plant hazards and analyzing the historical data took considerably longer than originally planned. The analysis and validation of the measurement data will be carried out in another paper, as well the creation of a digital twin of the instrumented wind turbine to generate EOC-independent measurement and simulation data [5], [6]. Both publications will also be presented at this conference and represent the subsequent work packages in the project plan.

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