

**Predictive Maintenance for Wind Power Systems**

Bachelorarbeit

von

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Prüfer: \*Titel Vor- und Nachname\*

Zweiter Prüfer: \*Titel Vor- und Nachname\*

Betreuer: \*Titel Vor- und Nachname\*

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Zusammenfassung

An dieser Stelle erfolgt eine knappe Zusammenfassung der vorliegenden Arbeit ([engl.] Abstract), die maximal ca. 200 Worte umfassen sollte. Der Sinn und Zweck dieser Zusammenfassung liegt darin, einem interessierten Leser die Entscheidung zu erleichtern, die vorliegende Arbeit überhaupt zu lesen bzw. vor dem Lesen der Arbeit erst einmal in Erfahrung zu bringen, worum es dabei geht. Also eine knappe, motivierende Hinführung zum Problem und wie Sie es gelöst haben.

Wenn Sie eine Zusammenfassung schreiben, bedenken Sie, dass diese oft auch alleine publiziert wird, d.h. sie sollte unabhängig vom nachfolgenden explizit dargestellten Inhalt der Arbeit für den Leser verständlich sein. Daher ist es immer sinnvoll, diese Zusammenfassung erst ganz am Ende zu schreiben, wenn Sie die eigentliche Arbeit bereits abgeschlossen haben.

test

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Abkürzungsverzeichnis (bei Bedarf)

An dieser Stelle **KANN!** ein Abkürzungsverzeichnis erfolgen, sofern angebracht

|  |  |
| --- | --- |
| AIFB | Angewandte Informatik und Formale Beschreibungsverfahren |
| KIT | Karlsruher Institut für Technologie |
| O&M | Operation & Maintenance |
| WPS | Wind Power Systems |
| WT | Wind Turbine |

Notationsverzeichnis (bei Bedarf)

An dieser Stelle **KANN!** ein Notationsverzeichnis erfolgen, sofern angebracht

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1. Introduction
   1. Motivation

According to the International Energy Agency (IEA) [1], electricity can be generated in two main ways:

1. **Thermal Power:** By harnessing the heat from burning fuels or nuclear reactions in the form of steam.
2. **Renewable Energy:** By capturing the energy of natural forces such as the sun, wind, or moving water.

With growing concerns over climate change, air pollution and fossil-fuel dependence, the need for renewable power generation has become more important. This has led to a significant shift toward renewable energy sources in recent years, with Europe’s renewable energy generation nearly tripling between 2004 and 2023 [2]. Although responsible for a mere 13.8% of European electricity generation in 2022 [1], **Wind Power** is among the **fastest growing** sources of clean energy. In 2023 alone, more than 18 Gigawatts (GW) of Wind Power was brought online and around 200 GW of new capacity should be installed from 2024-2030 [3].

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KI-generierte Inhalte können fehlerhaft sein.

Figure 1: Evolution of renewable electricity generation by source (non-combustible) in Europe [1]

This growth is not surprising because wind power comes with many advantages. It does not produce any carbon emissions during operation, helping to reduce climate change and air pollution. Additionally, it has lower costs compared to other forms of energy production since there are no fuel costs involved [4]. Wind power is also highly scalable, with the ability to be implemented both onshore and offshore, making it adaptable to various geographic locations. Furthermore, wind is an inexhaustible resource, ensuring long-term sustainability. These benefits have made wind power a key component of global strategies towards more sustainable, reliable, and environmentally friendly energy systems.

* 1. Problem

Despite its benefits, wind power systems face several operational and cost-related challenges. Wind turbines are often installed in remote areas, where access is difficult. Offshore wind farms can only be reached by helicopters or specialized vessels for maintenance, which are highly dependent on weather conditions. These factors can lead to longer repair delays, higher maintenance costs, and reduced energy reliability. Operation and maintenance (O&M) costs typically account for 25% to 30% of the total lifecycle costs of wind power systems [5].

To enhance reliability and reduce costs, efficient maintenance strategies hold great potential. Predictive maintenance methods may offer a solution by enabling early detection of potential issues, optimizing maintenance schedules, and minimizing both downtime and expenses.

* 1. Research Questions

RQ1: How can predictive maintenance and early fault detection increase the reliability of wind turbines?

RQ2: Which data sources can be utilized and how are the datasets strctured?

RQ3: Which methods and algorithms are used in literature to predict failures?

RQ4: What are the current challenges?

* 1. Beispiel Tabelle und Abbildung

Tabelle 1: Übersicht über XZY

|  |  |  |
| --- | --- | --- |
| Tabelle | Inhalt | X |
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|  |  |  |

Figure 2



Abbildung 1: KIT-Logo

1. Background
   1. Overview of Wind Turbines

Wind turbines convert the kinetic energy of moving air into electricity through various components. At the top of the tower, the nacelle houses the important elements like the gearbox, generator, and electronic controls. The turbine’s rotor consists of multiple blades attached to a central hub to catch the wind. When the wind pushes against the blades, it sets the rotor in motion. This rotational energy travels through the gearbox which steps up the rotor’s relatively slow spinning to a much higher speed for producing electricity. The high-speed shaft from the gearbox is connected to the generator, where the spinning motion is converted into electrical power. Within the nacelle, the yaw system aligns the turbine with changing wind directions, while the pitch system adjusts the angle of the blades, allowing for optimal efficiency and protection during strong winds. The tower beneath the nacelle is designed to provide support and put the rotors high in the air, where the wind is stronger and more consistent. Finally, control and monitoring systems ensure the turbine operates safely and efficiently, shutting it down in extreme conditions and restarting when it is safe. All these pieces work together so that wind turbines can provide a steady stream of clean electrical energy.

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Figure 3. Schematic of the mechanical components of a wind turbine [6]

Wind turbines convert wind energy into electricity using several interconnected components. At the core is the rotor, which has multiple blades attached to a hub body. These blades capture the wind, and their angle is adjusted by pitch mechanisms to optimize performance. Aerodynamic brakes help control the blades when needed. The mechanical energy from the rotor is transferred through the drive train, which includes rotor bearings, drive shafts, and couplings. In indirect drive turbines, a gearbox—made up of bearings, wheels, and a gear shaft—raises the rotor speed to a level suitable for the generator. In direct drive turbines, the rotor is connected directly to a low-speed, high-torque generator, reducing mechanical complexity and maintenance.

The nacelle, located at the top of the tower, houses the gearbox (in indirect drive systems) or the generator (in direct drive systems) along with important control systems. The yaw system, which includes yaw bearings, a yaw motor, wheels, and pinions, keeps the turbine pointed into the wind. A variety of sensors—such as anemometers, wind vanes, temperature sensors, oil pressure switches, power sensors, vibration switches, and revolution counters—continuously monitor the turbine’s performance. In addition, the hydraulic system, which consists of a hydraulic pump, pump motor, valves, and pipes or hoses, supports operational functions and safety measures.

The entire turbine is supported by a strong structure, including foundations, a tower secured with bolts, and a nacelle frame that comes with a cover and a ladder for access. Finally, an electronic control unit, along with relays and measurement cables, manages the operation of all these components to ensure safe and efficient energy production. Overall, these parts work together to provide a reliable source of clean electrical energy, with different drive system configurations offering benefits in design and maintenance.

* 1. Wind Turbine Failure Analysis

Wind turbines operate in harsh environments with fast winds and extreme cold or heat. Offshore wind farms beyond that are subject to corrosive sea air. This makes WTs **exposed** to a wide variety of faults. Although modern wind turbines are engineered to overcome a lot of load and stress, faults can still happen. More than 3800 WT failures have been reported annually, which lead to significant maintenance efforts and costs [5].

* + 1. Fault Tree Analysis

Combine these two

Fault Tree Analysis (FTA) is a systematic method used to evaluate wind turbine reliability by identifying potential failure events that could lead to critical outcomes such as shutdowns or malfunctions. It graphically represents the logical relationships between these failures using logic gates like AND and OR. In FTA, events are categorized into basic events, which are the most elementary failures, intermediate events resulting from combinations of basic or other intermediate events, and a top event that signifies the complete breakdown of the turbine system. This approach is widely applied to enhance the reliability and performance of wind turbines [7].

Wind turbine failure analysis often employs fault trees as a structured methodology to identify and evaluate potential causes of system breakdowns. Fault trees visually represent the logical interconnections between various turbine components, operational conditions, and environmental factors, enabling engineers to pinpoint root causes of failures systematically. This approach not only aids in designing more robust turbines but also supports proactive maintenance strategies by highlighting critical failure pathways. Consequently, fault tree analysis is instrumental in reducing downtime and optimizing the reliability and performance of wind energy systems [8].

Ein Bild, das Diagramm, Text, technische Zeichnung, Plan enthält.

KI-generierte Inhalte können fehlerhaft sein.

Figure 4 Fault Tree of a wind turbine system [7]

* + 1. Fault Causes

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Figure 5 Contribution of each component to the annual turbine downtime [9]

* 1. Maintenance Strategies

The overall maintenance cost is closely tied to the chosen maintenance strategy. It includes direct expenses, such as sensor investments and labor and indirect costs like downtime, lost production, and decreased equipment performance [5].

Maintenance is defined as “…”

The overall lifetime cost of a wind turbine can be broken down into the following three main components.

Capital Expenditure (CapEx), Operational Expenditure (OpEx) and Decommissioning Expenditure (DecEx). The OpEx includes Operation and Maintenance related costs. By the reducing the maintenance costs, which account for about… percent of the total costs.

However, there are several strategies, which can be used to ensure the healthy state of wind turbines.

Maintenance refers to the set of activities and processes aimed at ensuring that equipment or systems continue to operate reliably and efficiently throughout their lifespan. It involves inspecting, servicing, repairing, or replacing components to prevent failures and minimize downtime. In the context of wind power systems, maintenance plays a crucial role in sustaining energy output, reducing operational costs, and extending the life of turbines. Effective maintenance helps avoid unexpected breakdowns, enhances safety, and ensures that the turbines perform optimally under varying environmental conditions. There are several strategies

Maintenance strategies can be further divided into corrective maintenance and preventive maintenance. The preventive

* + 1. Corrective Maintenance

Corrective maintenance is a reactive strategy where equipment is only serviced after a failure, or a critical fault has occurred.

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Figure 6 Corrective (also known as reactive) Maintenance [10]

This approach minimizes initial maintenance expenses, by addressing issues only as they emerge. The approach might be acceptable for non-critical or low-cost assets. However, for wind turbines, it's not feasible because they represent a significant capital investment and are critical for energy production. Unplanned downtime can lead to substantial revenue losses due to interrupted power generation, while emergency repairs in remote or harsh environments can be both challenging and costly. Additionally, the complexity of turbine systems means that a failure in one component can lead to cascading issues, further compromising operational integrity and potentially endangering the safety of maintenance crews.

* + 1. Scheduled Maintenance

Preventive maintenance, often implemented through time-scheduled maintenance, is a proactive strategy that involves regular inspections, servicing, and component replacements based on predetermined schedules or usage intervals. This approach aims to address wear and potential issues before they escalate into major failures, thereby reducing unplanned downtime and extending the life of equipment. Although reventive maintenance typically incurs higher upfront costs compared to reactive methods, it offers more predictable maintenance expenses and improves overall operational reliability by ensuring that critical systems receive consistent care and attention.Ein Bild, das Text, Reihe, Diagramm, Screenshot enthält.

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Figure 7 Preventive (here as time-scheduled) Maintenance [10]

* + 1. Condition-based Maintenance

Condition-based maintenance is a proactive approach that uses real-time data and continuous monitoring to determine when equipment requires maintenance or repair. Instead of following a fixed schedule or waiting for a breakdown, sensors and diagnostic tools track key indicators to detect anomalies and potential failures. This enables maintenance teams to address issues at the most opportune time, reducing unnecessary service interventions while preventing major, costly breakdowns. By focusing on actual asset conditions rather than arbitrary time intervals, condition-based maintenance helps extend equipment lifespans, improve operational reliability, and optimize overall maintenance costs.

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Figure 8 Condition-based Maintenance [10]

* + 1. Predictive Maintenance

Predictive maintenance is an advanced strategy that leverages both real-time sensor data and historical performance trends to forecast when equipment is likely to fail, allowing maintenance to be performed just in time before any breakdown occurs. Unlike condition-based maintenance, which responds to the current state of equipment predictive maintenance uses sophisticated analytics and machine learning algorithms to analyze patterns and predict future failures. This forward-looking approach not only reduces unplanned downtime by scheduling interventions precisely when needed but also avoids unnecessary maintenance tasks that might occur with routine inspections. By combining a wealth of data from various sources with predictive modeling, organizations can optimize their maintenance schedules, improve asset reliability, and ultimately extend the life of critical equipment while reducing overall costs.

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Figure 9 Predictive Maintenance [10]

* 1. SCADA Data

SCADA, which stands for Supervisory Control and Data Acquisition, is an industrial control system.

Wind turbines are obliged to have a SCADA System since 2006 [11]. SCADA collects various operational data from wind turbine sensors at a 1 Hz rate. In most cases, it then aggregates these data points

over a ten-minute period into summary statistics like mean, maximum, minimum, and standard deviation. [11].

Armed with this data, wind farm operators can respond quickly to anomalies, adjust power generation, and proactively schedule maintenance to minimize downtime. Beyond immediate monitoring and control, SCADA data also forms the backbone of long-term analytics, enabling performance trend assessments, predictive maintenance planning, and fine-tuning of turbine operations for better energy yield.

This paper investigates if Supervisory Control and Data Acquisition (SCADA) can be used as a damage indicator and CMS. Since 2006, every wind turbine is obliged to use such a SCADA-system.

Wind turbines are obliged to have a SCADA System since 2006.

The lack of public datasets and a unified data structure is a major problem for researchers. Data sharing is not favored by wind turbine manufacturers and wind farm operators.. In particular, manufacturers see opportunities for adding value to their existing service business in the analysis of operational data.

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* 1. Anomaly Detection

Data-driven techniques rely on the fundamental theory of anomaly detection: the characteristics of a system’s data follow a consistent pattern during normal operation. When a fault occurs or begins to occur, the data generating process changes, and the data deviates from this pattern. By continuously monitoring and analyzing these changes, anomalies can be detected early, allowing for timely intervention before the fault leads to a larger issue [12].

Anomaly detection for wind turbine components involves monitoring sensor data to understand what normal operation looks like. Under regular conditions, sensor readings follow expected patterns because of the natural relationships between different parts of the turbine. When a fault occurs, the readings start to deviate from these patterns, resulting in measurable errors. Instead of using a fixed error limit—which might trigger false alarms due to normal fluctuations like wind gusts—an adaptive threshold is applied. This threshold adjusts based on the usual data variations, so it only raises an alarm when there’s a clear and sustained deviation from normal behavior, helping to catch problems early.

* 1. Algorithms and Methods for Predictive Maintenance / Machine Learning

Data Driven methods are seen as a key opportunity to forecast failures in Wind Turbines. While being difficult to interpret by humans, “they are the most suitable to perform the prognostic task of complex dynamic systems such as wind turbines” [13]. These methods can be categorized into two main ideas: Statistical Methods and Machine Learning methods. Statistical Methods include Moving Average, ARMA, Bayesian Filters and Particle Filters. Artificial Intelligence Methods aare RNN, ANFIS, SVR and HMM. These techniques generally do not rely on a detailed understanding of a physical degradation mechanism but instead use historical data and operational observations to infer machinery health trends and project remaining useful life (RUL).

Normal Behaviour Model

SCADA data serve as the foundation for developing a Normal Behavior Model (NBM). Once this model is established, any deviation from the expected operating pattern is flagged as an anomaly. The paper examines these anomalies prior to an actual failure in a wind turbine, where the failures themselves are documented by service reports [14].

1. Methodology

Here the goal is to explain the dataset im working on, and the different methods I want to compare. Then I do check how well these methods are suited for the given dataset. The most suited methods will then be tried out.

* 1. Data Acquisition

As described in the background section, acquisition of wind power SCADA datasets is not easy due to the reluctance of both wind turbine manufacturers and operating companies to share their proprietary data. This lack of public datasets poses hurdles for researchers aiming to develop advanced predictive maintenance methods. To address this gap, alternative data sources have been explored, such as the comprehensive GitHub repository "Wind\_Turbine\_SCADA\_open\_data" created by Simon Letzgus from TU Berlin, which, as of December 2024, lists 21 datasets. However, many of these datasets exhibit quality issues, including inconsistent sampling rates and missing data points. In this context, this thesis used the Care2Compare Dataset, provided by the authors of [15]. It was the most comprehensive and well described dataset.

* 1. Dataset Description

The used dataset is a combination of 3 individual datasets, with a common format. It consists of comprising 95 individual csv files that collectively represent 89 years of operational data gathered from 36 wind turbines distributed across three wind farms, referred to as A, B, and C.

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Figure 10 Key characteristics of the dataset [15]

Wind Farm A, located onshore in Portugal, contributes 22 datasets sourced from the EDP-open data platform, whereas Wind Farms B and C are offshore farms situated in Germany. Due to confidentiality requirements, the specific identities of Wind Farms A and B have been anonymized, and all dataset identifiers have been obfuscated accordingly.

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Figure 11 Directory structure of the Care to Compare dataset

Each wind farm directory contains a dedicated folder of datasets, in which every csv file corresponds to a single event that spans a segment of the turbine’s time series data. This dataset will no be referred to as sensor data, because it contains all the actual sensor values as a time series.These datasets are labeled as either “normal” or “anomaly,” leading to an overall distribution of 44 anomaly events and 51 normal events. The event\_info.csv file and the feature\_description.csv file will be referred to as metadata in the following.

* + 1. Sensordata

Within each dataset, sensor measurements are aggregated into 10-minute intervals. Every interval includes the average value, and for the majority of sensors also the minimum, maximum, and standard deviation. These measurements are supplemented by the metadata columns time\_stamp, asset\_id, id, train\_test, and status\_type which facilitate temporal alignment, turbine identification, partitioning of training and prediction segments, and the classification of operational modes (e.g., normal production, derated, downtime).

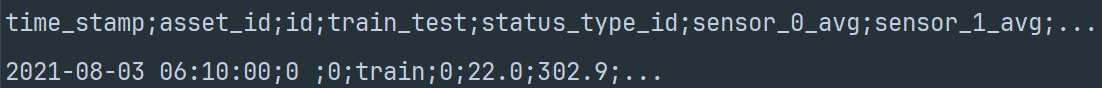


Figure 12 Shortened example of each datasets csv-file structure

* + 1. Metadata - Events

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Figure 13 Example of an Event of Wind Farm B transformed into JSON format

Additional context is supplied by an event\_info.csv file for each wind farm, which details the start and end points of each event, its assigned label (normal or anomaly), and, for certain anomaly events, the underlying root cause

* + 1. Metadata - Sensors

The feature\_description.csv file contains the sensor data information for each Wind Farm. Here, the sensors from the dataset csv file are mapped to their information by the sensor\_name. The file then provides a description of the sensor, the aggregation properties, the unit and if the sensor measures an angle or is a counter.

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Figure 14 Example of a Sensor measurement from the Wind Farm B transformed into JSON format

* + 1. Labels

The data is labelled on

* + 1. Suitability for Predictive Maintenance

3.3 Methods Compare

SVM, RNN, CNN, etc…

* 1. Data Preprocessing

Preprocessing the data is very important to extract features…

* 1. Modeling

1. Implementation
   1. Description of the Goal
   2. Python Programming
      1. Data Preprocessing
      2. Data Visualization
      3. Modeling the Machine Learning Tasks

The code from this bachelors thesis will be available

1. Results
2. Discussion
3. Conclusion

Anhang (bei Bedarf)

An dieser Stelle **KÖNNEN!** verschiedene Anhänge erfolgen, sofern angebracht.

1. Überschrift1

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1. Überschrift1

Hier steht Text.

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Erklärung

*Ich versichere wahrheitsgemäß, die Arbeit selbstständig verfasst, alle benutzten Hilfsmittel*

*vollständig und genau angegeben und alles kenntlich gemacht zu haben, was aus Arbeiten*

*anderer unverändert oder mit Abänderungen entnommen wurde sowie die Satzung des KIT*

*zur Sicherung guter wissenschaftlicher Praxis in der jeweils gültigen Fassung beachtet zu*

*haben.*

Karlsruhe, den 1. March 2025 VORNAME NACHNAME