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# Lifetime Analysis of a Wind Turbine Component

Master's thesis in Sustainable Energy Systems

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MASTER'S THESIS

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## ABSTRACT

The design life of a wind turbine is often said to be around 20 years. In practice it is frequently observed that components in a turbine fail earlier and must be replaced before the stated lifetime. Therefore, it is very important for the stakeholders of wind turbines to have a good estimation of the components remaining lifetime and create a suitable maintenance schedule. By possessing that knowledge, preventive measures can be taken to reduce the stakeholder's losses.

The purpose of this thesis was to investigate how the remaining lifetime of a wind turbine component can be estimated based on online measurement data. This included a study on whether the initially designed lifetime of a wind turbine component differed when the turbine had been in operation for some period of time. It was also of interest to find out if turbine owners have enough information regarding their turbines in order to perform similar studies.

The project was divided into two parts. In the first part a direct drive multi-MW wind turbine was studied. Lifetime calculations were performed for the main bearing, which is placed on the turbine shaft. However, some necessary measurements were missing and it was investigated whether a correlation to another signal could be found. In the second part of the project, five qualitative interviews were conducted with wind turbine owners with a varied range of installed capacity.

A correlation to the measured blade root flapwise bending moment was found and the lifetime calculation was performed. The designed lifetime of the main bearing differed substantially compared to when the turbine had been in operation for some period of time. From the lifetime calculation it was found that different wind speeds affect the wear of the main bearing differently. The highest wear of the main bearing occurred close to the rated wind speed.

If similar calculations were implemented for other components the operator of a wind turbine would get a better picture of how different operating conditions influence the wear of different components. As a result, the owner could decide how the turbine should operate during the most destructive wind speeds.

From the interviews it was found that the owners do not get sufficient information from the manufacturer in order to do similar studies. Some owners have tried to gain access to more information regarding their turbine, but to little avail as the manufacturers are unwilling to share this information due to competitive reasons.



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# Preface

This report is the result of a master thesis, which has been made as a completion of the the master's program in Sustainable Energy Systems at Chalmers University of Technology. It has been carried out for the division of Electric Power Engineering at the department of Energy and Environment. The thesis has been conducted in a cooperation between Chalmers and Greenbyte AB, a software company in the renewable energy sector. The thesis corresponds to 30 credits and has been carried out in a 20-weeks period between January and June 2016.

First of all, we would like to thank our supervisor Håkan Johansson for his invaluable advises and guidelines throughout the project. We have very much appreciated his enthusiasm, knowledge and interest in the subject.

We would like to thank our examiner Ola Carlsson for sharing his experience in the field, for always setting off time for discussions and for encouraging us in the work.

Furthermore, we would like to thank Sara Fogelström for providing us with essential material and for being helpful throughout the project.

We would also like to thank our supervisor Jonas Corné and the employees at Greenbyte for their support and hospitality.

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# 1 INTRODUCTION

## 1.1 Background

The modern day society is constantly changing and evolving, especially as a result of continuously emerging new technologies that require energy to function. The power sector, as well as the transportation and industry sectors, is mainly fuelled by the environmentally harmful fossil fuels. In recent years, there has been an increased emphasis on developing new technologies that can make use of renewable sources, thereby decreasing the usage of carbon emitting energy sources.

There are of course different opinions on the benefits of switching to a more sustainable power system. The main arguments against it are, for example, the reliability of supply and the difficulty of generating energy in large quantities. Renewable energy relies mainly on the weather for sources of supply, such as solar, wind and rain, which can be unpredictable. In case of shortcoming of the supply, the energy sources lack the capacity to produce energy. In addition, it is more difficult to produce large amount of energy from renewable sources compared to fossil fuelled powered plants. Therefore, more facilities must be constructed to keep up with the energy demand and new ways have to be found to reduce the energy consumption. In addition, fossil fuels usually have a higher energy density compared to the renewable sources and are therefore easier to handle. A big concern is the large amount of land required for the installations of the different energy sources, as well as many people are displeased with the visual pollution related to those installations. However, there are big advantages in investing in renewable energy. The energy production is clean and has little to no carbon emissions, as well as the natural resources will not diminish. An important part of its appeal is that it can reduce the dependency on fuels from other countries and stabilize the energy prices, in addition of being a cheaper and more economically feasible source of energy compared to other sources.

In recent years wind power technology has developed rapidly. It is viewed as a clean and environmentally friendly energy source with a relatively low cost. The technology has gained a lot of momentum as an important primary energy source contributing to a more sustainable energy system. Although the wind technology introduces many positive things to the energy sector, it also brings along uncertainties, such as environmental impacts, as well as how the optimal operation and maintenance plan should be structured. Even though the unknown factors concerning the wind technology are many, the impact the technology can have on the future energy system is considerable. It is therefore worth investing more time and resources on improvements in this field of study.

The design life of a wind turbine is often said to be around 20 years. In practice it is frequently observed that components in a turbine fail earlier and must be replaced before the stated lifetime. Therefore, it is very important for the stakeholders of wind turbines to be able to get a good estimation of a component's remaining lifetime so they can put up a suitable maintenance schedule and decide on how to exhaust the component in the most optimal manner. By possessing that knowledge, preventive measures can be taken to reduce the stakeholder's losses. However, it is unclear how much information concerning the turbines the owners have access to, this can limit their possibility of analysing their turbines.

## 1.2 Project description

The thesis can roughly be divided into two parts. The first part examines the operation of the wind turbine itself while the second part focuses on the "information flow" between different actors concerning the design aspect of the technology.

In the first part, the main focus was to investigate how the remaining lifetime of a wind turbine component can be estimated based on online measurement data. There are many different factors influencing the actual operation of the turbine and one must be careful to not put too much faith in the manufacturer's expected operation of the turbine. Therefore, it was of interest to compare how, or if, the initially designed lifetime of a component differed when the turbine had been in operation for some period of time.

Access to design documents and simulations for a specific wind turbine was granted. It included information about the design of the turbine as well as information of its expected performance. In addition, measurement data from different sensors placed on the turbine was provided. The measured data represent the actual performance of the turbine, i.e. when the turbine has been in operation for a period of time.

The wind turbine considered in this thesis is a direct drive multi-MW wind turbine and it was decided to focus on the main bearing, which is positioned on the shaft.

The lifetime equation used in this project is straight forward, and it is relatively simple to perform the calculations. However, the project took a turn when an essential parameter needed in the equation was missing from the measured data. Therefore, the focus was put on finding a correlation between that parameter and another signal that existed in the measurement programme. In that way the missing parameter could be calculated and so the lifetime estimation was performed.

The second part of the thesis involved conducting interviews with owners of wind turbines. The purpose of those interviews was to find out what kind of information the manufacturer is willing to give to the buyer of their turbines. It was of interest to examine if wind turbine owners have the possibility to do similar calculations as were made in this thesis. Factors such as if the size and ranking of the company played a part in the flow of information were looked into as well as how, or if, turbine owners used this information for their turbine's operation and maintenance. Five qualitative interviews were conducted with wind turbine owners with a varied range of installed capacity.

## 1.3 References in the text

In this thesis, it is investigated if the initially designed lifetime of a wind turbine component differed when the turbine had been in operation for some period of time. Wording such as simulated data and expected performance is related to the initial design of the turbine. Measured data, real life data and actual performance is related to the case when the turbine had been in operation for a period of time.

The bearing considered in this project is the front main bearing. In this project it will be called the main bearing.

The force acting parallel to a turbine's main shaft is commonly named the thrust force or the axial force. In this report the name axial force is used.

The design document and the data used in this project are confidential. Therefore, all graphs have been scaled according to the following conditions.

<b>Parameter</b>	<b>Condition equal to unity</b>
Axial force:	Simulated axial force at 12 m/s
Radial force:	Simulated radial force at 3 m/s
Flapwise bending moment:	Simulated flapwise bending moment of Blade 3 at 12 m/s
Edgewise bending moment:	Absolute value of the simulated edgewise bending moment of Blade 3 at 17 m/s
Rotor speed:	Simulated rotor speed at 12 m/s

## 2 THEORETICAL BACKGROUND

### 2.1 Developments of wind turbines

In recent years, researches in wind turbine technology have increased rapidly as a result of an increased interest in reconstructing the energy system into a more sustainable one. Figure 1 shows how the global installed wind capacity has escalated swiftly in the last years.

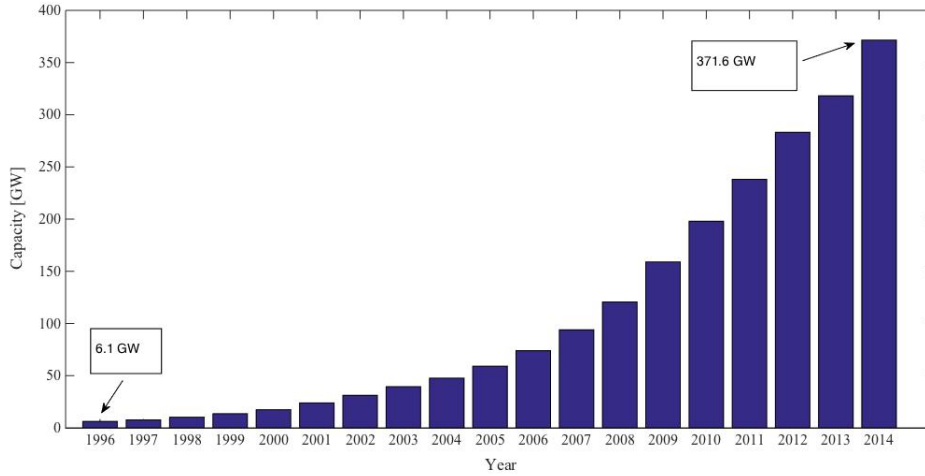


Figure 1: Total global installed capacity of wind power between 1996-2014 (Amended from [1] and [2])

The profitability of a wind energy project is determined by factors such as available wind resources, the wind turbine type, the cost of connecting to the grid and the operational and maintenance plan [3].

The size of wind turbines has increased considerably over the last decades. The main reason for this transformation is that the energy output from the bigger wind turbines are substantially larger than from a smaller model while it does not require as high installation cost to manufacture bigger turbines. In addition, larger turbines can harness wind energy higher from the ground, which is where the wind is stronger. The power ratings of wind turbines are mostly ranging from 250 kW to 7 MW [4].

The implementation of offshore installations has increased over the last years. One of its advantages is that the offshore wind is stronger and blows more consistently than land based wind. In many suitable locations, the water is too deep for it to be practical to build conventional foundations. In those locations, floating offshore wind platforms are used. The construction cost of offshore turbines is high due to the frequently extreme weather conditions. The turbines must be designed more robust compared to the land based turbines in order to reduce the downtime, as the maintenance cost is much higher for offshore turbines. In order to take advantage of the steadier offshore winds

and to increase the economical viability of the offshore turbines, they must be built larger than the land based turbines [5]. Presently, developments of 10 MW offshore wind turbines are taking place [4].

The wind power technology has improved continuously ever since it first emerged. Advancements in wind technology together with supportive policy measures can significantly increase the development and implementation of wind turbines. It is important that there exists a reliable, long-term policy from the government concerning wind technology. By having that, investors are much more likely to see the benefit by investing in the technology and therefore more technological improvements are to be made. In addition, developments, such as finding ways to store large quantity of surplus electricity, can have a big impact in establishing a solid foundation for wind technology in the future energy system [6].

## 2.2 Design of a wind turbine

Wind turbines are divided into two main design categories, the vertical axis wind turbine and the horizontal axis wind turbine. In the wind industry, the horizontal axis wind turbine dominates as it utilises the wind more efficiently [7]. Furthermore, there are a number of challenges in scaling up the vertical axis wind turbine to a commercial scale. For example, their design is not as robust compared to the horizontal axis wind turbine [8]. However, the wind flow has to hit the horizontal axis turbine at a certain angle in order to work properly. To respond to the changes in the wind direction the horizontal axis wind turbine has a yaw drive, which keeps the rotor facing the wind. The vertical axis wind turbine works well regardless of the wind direction and is therefore less mechanically complex [7].

This thesis revolves around a horizontal axis wind turbine. Therefore, hereafter when mentioning the wind turbine it refers to an horizontal axis wind turbine.

Wind turbines convert the kinetic energy in the wind into mechanical power, which a generator then converts into electricity. The amount of energy a wind turbine can utilize from the wind is mainly dependent on three factors; wind speed, air density and the swept area of the turbine blades. The wind power is calculated using Equation 1 [9].

$$P_{wind} = \frac{1}{2} \dot{m} V^2 = \frac{1}{2} \rho A V^3 \quad [W] \quad (1)$$

The three aforementioned factors are represented in the equation as:

$A$ =rotor disk area, [m<sup>2</sup>]

$\rho$ = air density, [kg/m<sup>3</sup>]

$V$  = wind speed, [m/s]

Furthermore,  $\dot{m}$  is the mass flow rate of the air and is a function of all three factors.

As can be seen from Equation 1, the wind speed is an important factor in determining the wind power as the power varies with the cube of the wind speed. A small change in the wind speed will have a big impact on the available wind power. Wind speeds depend on altitude, a commonly adopted formula is given as [9]

$$V_2 = V_1 \left( \frac{h_2}{h_1} \right)^\alpha \quad (2)$$

where

$V_2$  is the average wind speed at the measurement height  $h_2$

$V_1$  is the average wind speed at the measurement height  $h_1$

$\alpha$  is the wind shear exponent.

The equation shows that the wind speed increases with higher altitudes, therefore wind turbines have gotten a taller structure to take advantage of those higher wind speeds. In addition, the difference between wind speeds at different altitudes increases by increased wind speeds. This is a result of Equation 2 not having a linear relation, as can be noted from the wind shear exponent. The wind shear is often assigned a value of 0,143 to predict wind speeds in a well mixed atmosphere for a flat and open terrain. The value will increase for vegetated terrain and when wind speeds are light to moderate [10].

The density of the air is an important factor to consider in relation to the wind power, as can be seen from Equation 1. The denser the air, the more energy is received by the turbine. The air density is dependent on the temperature and elevation. Air is denser at lower elevations and at colder temperatures.

A larger swept area of the turbine blades means that the turbine can capture more power from the wind. The swept area increases with the square of the rotor diameter. Therefore, by doubling the rotor diameter, the swept area will become four times larger and consequently, the power potential will increase considerably [11].

To get a better understanding of the theory and the basic components in a wind turbine Figure 2 was constructed. It illustrates the swept area of the blades as well as where the main components and connections are positioned.



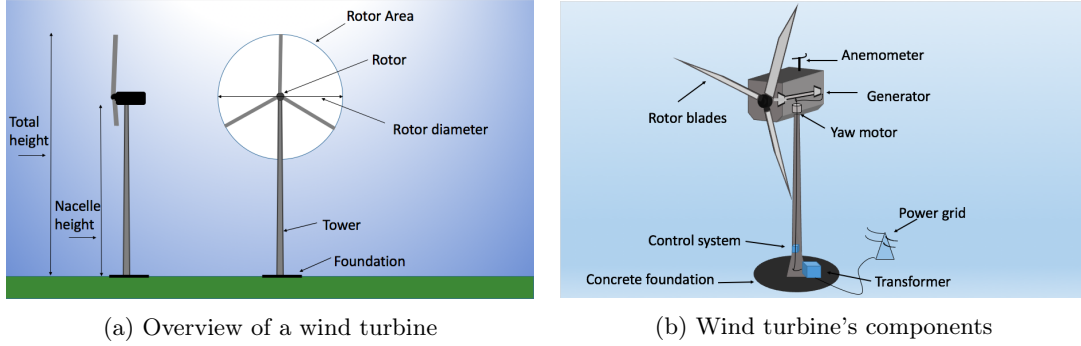


Figure 2: Wind turbine's basic structure and components (Amended from [9])

The turbine's power coefficient,  $C_p$ , is an important factor to consider when estimating how much power the turbine can extract from the wind. It is a measurement of how efficiently the turbine converts the energy contained in the wind into electricity. The power coefficient is explained by the relation given in Equation 3 [9].

$$C_p = \frac{\text{Electricity produced by the wind turbine}}{\text{Total energy available in the wind}} \quad (3)$$

The power coefficient is a measure of a turbine's overall system efficiency as it represents the combined efficiency of different turbine components, such as blades, shaft bearings, generator and the power electronics. The turbine manufacturers calculate the power coefficient for each turbine and it is usually given at various wind speeds. The power coefficient varies with different operating conditions, such as wind speed and the turbine blade angle [12]. The power the wind turbine can extract from the wind is found in Equation 4 [9].

$$P = \frac{1}{2} \rho A C_p V^3 \quad [W] \quad (4)$$

Where

$A$ =rotor disk area,  $[m^2]$   
 $\rho$ = air density,  $[kg/m^3]$   
 $V$  = wind speed,  $[m/s]$   
 $C_p$ =Power coefficient

Similar to Equation 1, the wind speed is a determining factor in the power output. The maximum value of the power coefficient is 0.593, i.e. no wind turbine can convert more than 59.3% of the wind's

kinetic energy into mechanical energy by turning a rotor [9]. This restriction is called the Betz 's limit. The wind upstream of the turbine moves faster than the wind downstream of it. The wind starts to slow down even before it reaches the blades and so the available power is reduced. Furthermore, some of the wind diverts around the slower moving air and misses the rotor entirely. Due to these issues it is not possible to extract all of the power in the wind. New wind turbine designs have the power coefficient in the range of 0.4-0.5 [13].

Wind turbines are designed to endure extreme wind speeds. They have a certain cut-out wind speed limit so when the wind speed exceeds that limit the turbine will stop turning. However, there are many different wind scenarios before the cut-out limit that influence the turbine's operation. The turbine uses control systems to cope with high wind speeds that could cause harm to the turbine. These control systems vary between different wind turbines and they are divided into active and passive control systems [14]. The thesis revolves around a pitch regulated wind turbine, which is a type of an active control system.

Wind turbines are usually designed to yield maximum power output at wind speeds around 15 m/s. Higher wind speeds are rather uncommon but when they happen, a power control system is used to waste part of the excess energy in order to avoid damaging the wind turbine. An electric controller in a pitch controlled wind turbine checks the power output of the turbine several times every second. When the output is too high the blades are pitched out of the wind, the blades are then pitched back into the wind when the wind speed gets lower. In this way, an optimal power output can be obtained for every wind speed [15]. Figure 3 gives a rough overview how the power output from a pitch-regulated wind turbine varies with wind speed.

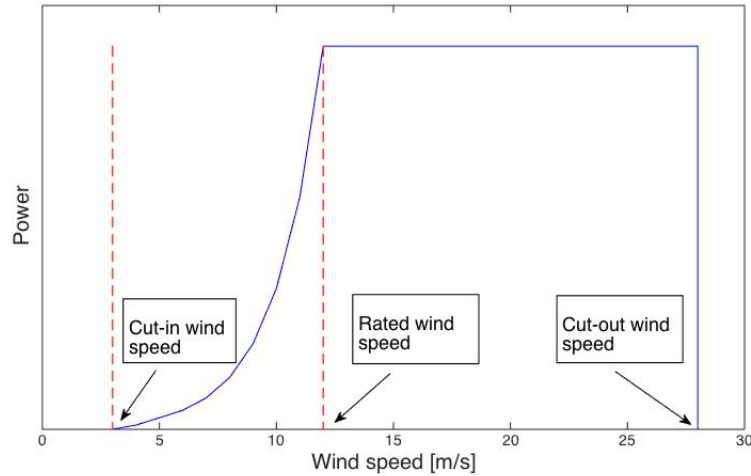


Figure 3: Pitch regulated wind turbine's power output (Amended from [9])

The cut-in wind speed represents the minimum wind speed at which the turbine starts to generate electrical power. The generator's output limitation is called the rated power output. The lowest wind speed which produces the rated power is called the rated wind speed. As previously mentioned, at the cut-out speed the turbine stops producing power and shuts down to avoid damage [16].

The thesis is based on a direct drive wind turbine. That means that the turbine lacks a gearbox, which is assumed to be one of the most complicated part of the machine and the part that is most prone to experience maintenance difficulties. The less complicated design of the direct drive turbine is one of its main advantage as the rotor drives the synchronous generator directly. As a result, the generator has a lower rotational speed compared to using the gearbox technology as well as the machine is less vulnerable and the operation and maintenance becomes easier [17]. However, it is more expensive than the gearbox technology. The permanent magnet generators, which are often used in direct drive wind turbines, are very large and heavy and therefore expensive to built, transport and install. Furthermore, these permanent magnets are made of rare earth metals which increases the cost [18]. However, recent improvements of the technology have decreased the cost [17].

### 2.2.1 Blade design

The wind turbine blades are designed to maximize the turbine's power output and at the same time minimize the cost of the blade. Unfortunately, there is a trade off between the aerodynamic efficiency and the structural efficiency of the turbine blades. To reach the optimal aerodynamic efficiency the blades should be very thin, but this means that the structure of the blade must be made stronger and stiffer, which often results in a higher cost. Therefore, the blade designer has to compromise between the cost of the material and the power efficiency of the blade. In general, the blade is thicker than the aerodynamic optimum at the blade root because there the material experiences the most stress due to bending [13].

The number of turbine blades is another important design factor to consider. With an increased number of blades the aerodynamic efficiency increases. However, the gain in aerodynamic efficiency decreases for every additional blade. By for example increasing the number of blades from two to three the gain in aerodynamic efficiency is 3% and by increasing the number of blades to four the gain in efficiency is only 0.5%. In addition, the side effect of increasing the number of blades is an increased cost. Furthermore, with a higher number of blades, the blades need to be thinner in order to be aerodynamically efficient. This leads to higher requirements of the blade structure as previously discussed. Generally, three bladed wind turbines, which can accommodate a thicker root to withstand high wind loads, are used [19].

In order to prevent the blades from hitting the tower of the wind turbine several actions are performed. The blades are placed at a certain distance in front of the tower and the turbine shaft is tilted up at a small angle. Furthermore, the blades can be coned away from the tower, which means that the blade connection to the hub has a small angle out of the rotor plane. The blades can also be curled out of the rotor plane [20].

The turbine's rotor speed has to be controlled so that it gives maximum power output while rotating in a way that is not harmful to the turbine. The relation between the speed of the rotor and the wind speed is called the tip speed ratio, TSR. It is defined by the following relation [9].

$$\text{TSR} = \frac{\text{Tip speed of blade}}{\text{Wind speed}} \quad (5)$$

In order to extract as much power as possible from the wind the wind turbines must be designed to operate at their optimal tip speed ratio. When a turbine blade cuts through the air it creates turbulence wake in its path. If the turbine blades rotate too fast the next turbine blade will hit turbulent air. This will cause vibrations and stresses in the blade and it will not be able to extract power from the wind in an efficient manner. To avoid this the tip speed ratio needs to be chosen in a way that the rotor blades do not pass through turbulent air [21]. Furthermore, the tip speed should not exceed the speed of sound to avoid creating shock waves [22].

When the wind turbine is stationary, the direction of the wind seen from the wind turbine's blade is the same as the undisturbed wind direction. However, as soon as the rotor of the turbine has started to move, the wind direction as seen from a point on the turbine blade changes. The wind velocity seen from the rotating blade is called the relative wind velocity or the apparent wind speed. It is the resultant vector of the undisturbed velocity vector and the tangential velocity vector of that point on the blade [23]. The apparent wind speed is represented in vector form in Figure 4.

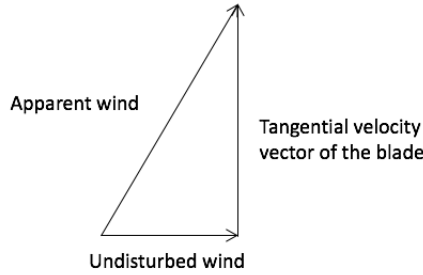


Figure 4: The apparent wind represented in vector form

The angle between the apparent wind speed and the chord line of the blade is called the angle of attack. A turbine's blade works in a similar way as an airplane wing, a lift force is created perpendicular to the air flow and a drag force parallel to the air flow [13]. The lift force, drag force and the angle of attack are illustrated in Figure 5.

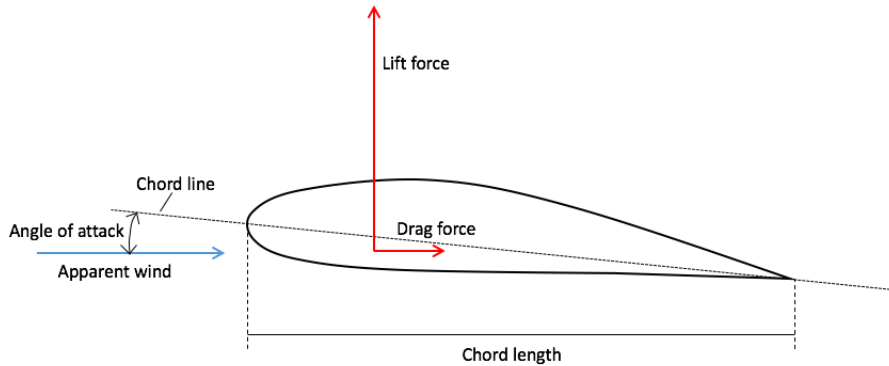


Figure 5: Lift-and drag forces acting on a turbine blade (Amended from [13])

The lift force increases as the angle of attack increases, the angle is changed by pitching the blades. At a very large angle of attack the turbine blades stall and the lift force decreases again. The lift force is desired since it contributes to the rotation of the turbine blade. The drag force is however unwanted since it opposes the rotation of the blades. Unfortunately, the drag force also increases with increased angle of attack. At very high angles of attack the drag force increases dramatically, especially when the blades stall. Therefore, at an angle slightly less than the maximum lift angle, the maximum lift-to-drag ratio occurs. The optimal operation point will be between these two aforementioned angles. Furthermore, if the airfoils have a good design the lift force is much bigger than the drag force [13].

Modern wind turbines have a twist along the length of the blade. The wind turbine blade rotates with the lowest velocity at the hub and the velocity increases along the blade. The apparent wind direction changes when the speed of the blade increases, therefore to keep an optimal angle of attack along the full length of the blade the blade needs to be twisted [24].

## 2.3 Design requirements of wind turbines

Wind turbines must follow a technical standard that states common rules and guidelines. The turbine this thesis revolves around follows the IEC 61400-1 standard. That standard specifies essential design requirements for wind turbines, which includes engineering design protocols, testing of components, evaluating site conditions, etc. The standard is implemented to provide an appropriate level of protection from damage of the turbine and its sub-systems throughout the expected lifetime. The implementation of standards in a turbine's design process is an important part in financing new wind turbine projects. The standard offers the investors a sense of trust in both the turbine design and their decision to invest in the turbine.

The following sub-chapters will refer to the IEC 61400-1 standard [25].

### 2.3.1 Design documentation and dynamic simulations

Before a decision is made about erecting a turbine at a particular site, simulations are required to estimate the site's feasibility. The simulations predict loads over a range of different wind speeds and for different operating conditions. The simulations are made by using a structural dynamic model, which includes, for example, turbulence models, aerodynamic models and control algorithms for yaw and braking actions. By using these models one can simulate various wind and operational conditions, which is an essential part of the wind turbine's design process [26]. In addition, the IEC 61400-1 standard states a range of other specifications that the model is required to include. The results from the simulations must be clearly stated in a design documentation, which every turbine has. The design documentation contains results from the simulations for different load cases, which are roughly divided into fatigue load cases and extreme load cases. The different load cases are determined by

combining various operational modes or other design situations with external conditions affecting the turbine. The simulated data sets are probability functions as they inform how many percent of the total lifetime a certain load case is expected to occur over the span of 20 years. Furthermore, it estimates the wind distribution within each load case.

Wind turbine's lifetime estimation includes all of the design load cases and their probability of occurring during the time period in question.

For the particular design documentation obtained for this project, it was assumed that the wind speed distribution is similar for each year during the turbine's lifetime. Therefore, the stated 20-year period wind distribution was used to represent a one-year wind distribution.

## 2.3.2 Wind classes

The external conditions that have to be considered when designing a wind turbine are dependent on the turbine's location. The wind will behave differently at various sites and therefore each wind turbine is categorised into a specific wind class. The main parameters to categorise wind classes are the wind speed and turbulence intensity. There are three main wind turbine classes, which aim to cover most applications. Furthermore, a wind class represents many different sites and does therefore not refer to a one specific site.

When a special wind condition or other external conditions are present at a site a further turbine class needs to be implemented, which is called wind class S. The design parameters of class S are determined by the designer and should be stated in the design documentation together with a description of the model used to obtain these values. Conditions that may require a class S are for example tropical storms or offshore conditions. Class S is also used if special safety classes are required by the designer or costumer. Table 1 illustrates the basic parameters for the wind turbine classes for conditions at hub height.

Table 1: Wind turbine classes

Wind turbine class	I	II	III	S
$V_{ref}$ (m/s)	50	42.5	37.5	Values specified by the designer
A (-)	0.16			
B (-)	0.14			
C (-)	0.12			

Where

$V_{ref}$  = the average wind speed over 10 minutes with a recurrence period of 50 years. The wind turbine is designed to withstand climates at which the wind speed at hub height is lower or equal to  $V_{ref}$ .

A, B, C = higher, medium and lower turbulence characteristics respectively. Their values are the expected turbulence intensity at 15 m/s.

There are several other parameters required to cover all the external conditions for different wind classes. Those parameters are for instance air density, humidity and ambient temperature. The wind turbine should be designed to withstand wind conditions defined by the selected wind class. For wind turbine classes I to III, i.e. the standard wind turbine classes, the design lifetime should be at least 20 years.

## 2.4 Maintenance

In order to maximize the profits from a wind power project the turbine must be available for as long time as possible. Faults in a wind turbine causes unavailability, i.e. downtime, which means that the turbine is unable to produce energy, which leads to economical losses. In order to avoid downtime, it is important to perform a maintenance before the fault occurs, hence preventing failures in the turbine. This is however not always possible. Therefore, when a fault occurs it is necessary to perform a maintenance quickly in order to minimize the downtime and thereby reduce the losses.

In the Reliawind project, which was run from March 2008 to March 2011, the reliability of large wind turbines was investigated. The failure rates and downtimes from operational wind turbines were measured and critical sub-systems were identified. The project included 450 wind farm months of wind turbine data involving 350 wind turbines operating for a varying length of time. The data was collected from both onshore and offshore wind turbines [27]. It included 10 minute SCADA data, which is automated alarm-logs and service records along with detailed data provided by wind turbine manufacturers. Around 35000 downtime events were identified during the project [28]. Results from the project can be seen in Figure 6. The figure visualizes to how big extent the different sub-systems are contributing to the total downtime of a turbine during one year.

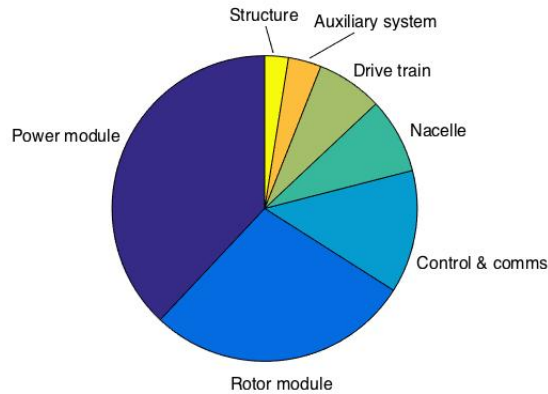


Figure 6: The different sub-systems contribution to the overall downtime, in percentage lost hours per turbine/year (Amended from [28])

Figure 6 shows that the power module is the sub-system that causes the longest downtime followed by the rotor module. Each sub-system represents a number of components or systems. Figure 7 gives a rough estimate of the components/systems which are causing the longest downtime. The section "Other" contains a collection of components/systems each contributing to a minor downtime and is therefore grouped together to make the chart clearer.

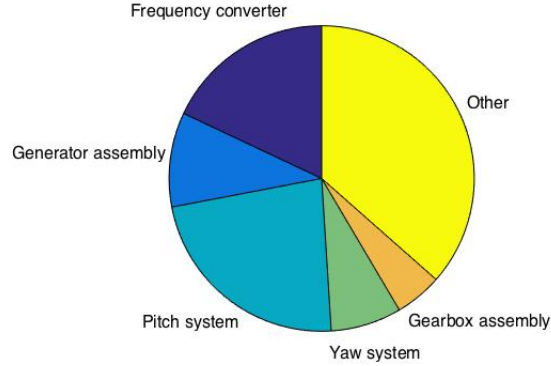


Figure 7: Components or systems contribution to the overall downtime, in percentage lost hours per turbine/year (Amended from [28])

In a wind turbine project, the owner receives a warranty from the original equipment manufacturer. Performance-, mechanical-, availability-, electrical and environmental issues are commonly included in the warranty. Since 2008 the standard wind product warranty has increased from two to five years [29].

In order for a wind power plant to have a strong long-term performance a maintenance plan should be implemented. The maintenance plan needs to be reliable and cost-effective in order to ensure an efficient operation of the turbines and its infrastructure throughout the turbine's lifetime. When the warranty has expired the owner has several options for the operation and maintenance of the turbine. These options include an extension of the warranty period, purchase of a service package from the original equipment manufacturer, purchase of a service package from third party contract or conduct the maintenance themselves, i.e. in-house maintenance [29].

The maintenance of a system can be divided into two categories: corrective maintenance and preventive maintenance. The corrective maintenance is carried out after a fault occurs and aims to put the item into function again. The preventive maintenance is carried out before a failure occurs, it is divided into two sub-categories: scheduled maintenance and condition based maintenance. The scheduled maintenance is performed at predetermined intervals and the condition based maintenance is performed according to prescribed criteria [30]. In systems with age related failures and where an accurate probability density function of failures can be estimated, the scheduled maintenance can typically be applied. The condition based monitoring can be beneficial for components which show signs of degradation before an eventual failure [31].

Another type of maintenance is the opportunity based maintenance. This type of maintenance typically takes place at the same occasion as a corrective maintenance and is typically performed in a preventive manner. The opportunity based maintenance is getting more attractive for offshore wind farms as it is expensive gaining access to those wind turbines [31].



The access to data is essential for an efficient operation and maintenance of a wind turbine. The trend has shown a movement towards a higher usage of condition based-and opportunity based maintenance. For the development of improved operation and maintenance methods, the SCADA (Supervisory Control And Data Acquisition) and condition based maintenance will play an important role [32].

# 3 EVALUATION OF THE TURBINE'S PERFORMANCE

## 3.1 Computer programmes

The lifetime calculations performed in the thesis are based on simulated and measured data, which was processed in two different computer programmes. The simulated data represent the expected performance of the wind turbine while the measured data represents the actual performance. Due to the restricted time of the project, only one design load case was investigated, which was the normal power production case for fatigue loads. When the wind turbine is in the normal power production mode there are no unexpected faults or downtime of the turbine present. Additionally, the wind speed is between the cut-in wind speed and the cut-out wind speed, which means there are no start-ups or shut-downs included in the load case.

The simulations were carried out in the ScanSim simulation setting based on the aero elastic code Vidyn. It is a simulation programme based on static and dynamic structural analysis for a horizontal axis wind turbine. In Vidyn, forces and movements are calculated as functions of time for given wind- and operating conditions [33]. The data collected from Vidyn was extracted through a programme called Fplot, which gave a visual display of the outputs from the signals of interest. The simulated data was constructed so that there were six simulations for every wind speed, where each simulation set was based on ten seeds per wind speed. For this project, only the outputs of the simulations were treated, thus the programme Fplot was used. Figure 8 gives a rough overview of the computer programme Fplot.

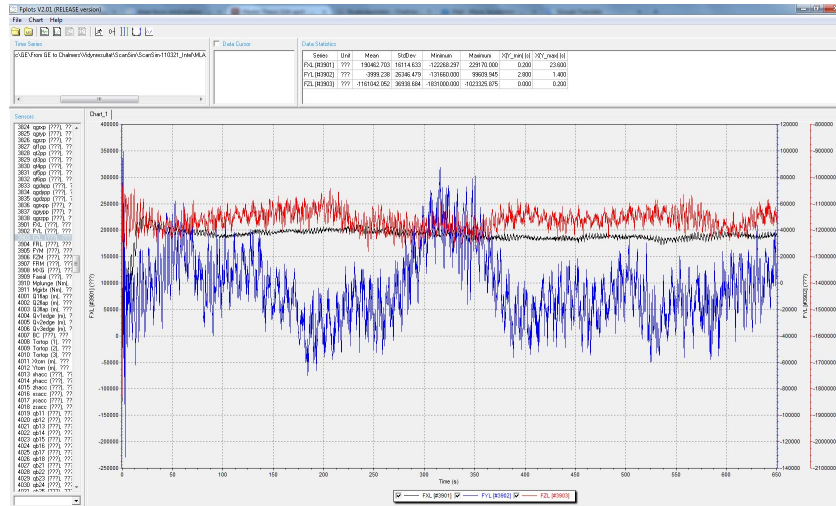


Figure 8: Screen capture from the computer programme Fplot

An access to a one-year long measurement data was granted. The measured data was extracted from the programme `imc FAMOS`, which is a data analysis software. The programme offers the possibility of analysing different wind outputs at certain time intervals. The data was then extracted from `FAMOS` and processed in `MATLAB` for further analysis. Figure 9 gives a rough overview of the computer programmes `FAMOS` and `MATLAB`.

(a) FAMOS

(b) MATLAB

### 3.2 Comparisons between different anemometers

In this case, a meteorological mast was raised with a number of anemometers installed on different locations on vertical boom. The anemometers monitored undisturbed wind characteristics such as wind speed and wind direction. All of the anemometers fulfilled the sensor requirements stated in

the IEC 61400 standard. Furthermore, an anemometer was positioned on the turbine's nacelle. It was of interest to find out whether the nacelle anemometer and the mast anemometer would give similar measurements. Figure 10 shows the average wind distribution over the one year period for the nacelle anemometer and for one of the mast anemometers.

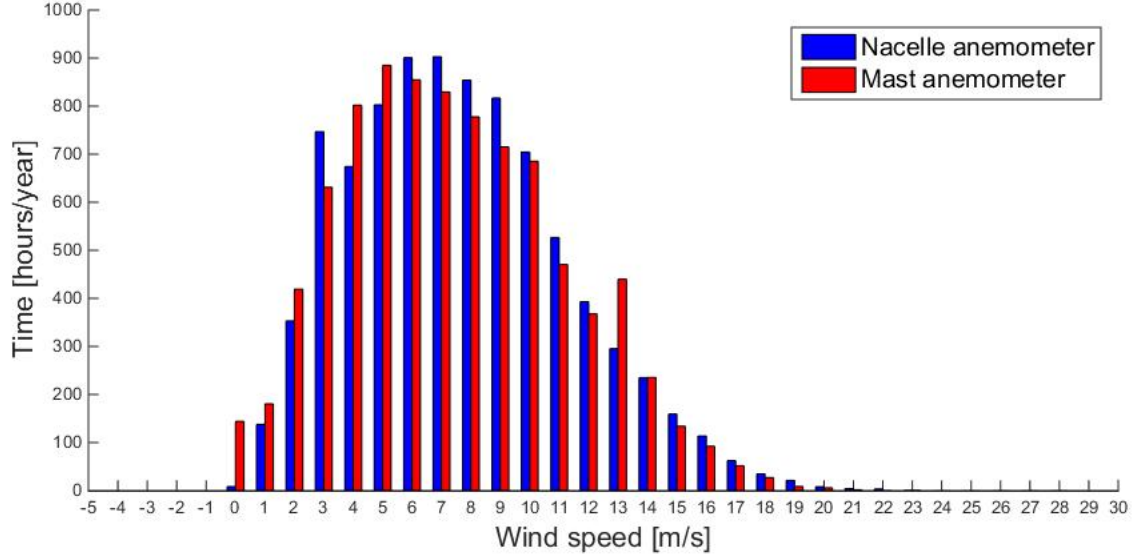


Figure 10: Wind distribution over one year for the nacelle anemometer and a mast anemometer

The nacelle anemometer is situated at the hub height of the wind turbine while the mast anemometer is placed slightly higher, although within the allowed deviation range of 2.5% [35]. The figure shows how there is little difference between the average wind speed distribution over the one-year period for the two anemometer locations. However, the figure gives an unexpected outcome as the nacelle anemometer gives slightly higher measurements compared to the mast anemometer for some wind speeds. This comes as a surprise as studies have shown that nacelle anemometers give significantly lower data measurements compared to mast anemometers [36]. Mast anemometers measure the undisturbed wind characteristics while nacelle anemometers are sensitive to factors such as the position of the nacelle along with operating conditions such as inflow or turbulence of the wind as well as changes in the turbine control. Therefore, the nacelle measurements can lead to an incorrect performance monitoring [37]. There are however cases where the nacelle anemometer gives more favourable measurements compared to the mast. Possible explanations for that behaviour is that the wind is affected by the nacelle so that the wind speed increases at the anemometer or that some sort of a scaling is used on the nacelle anemometer [38]. To get a better understanding on the importance of selecting a reliable anemometer to base measurements on, one can look at the measurements for the cut-in wind speed, which is the minimum wind speed at which the turbine starts to generate power. For the nacelle anemometer, 14,2% of the year the average wind speed is under the cut-in wind speed compared to 15,7% of the year for the mast anemometer. That means that in this case the nacelle anemometer gives a lower total annual downtime of the turbine, meaning no power production, compared to the mast measurements. In other words, the nacelle measurements gave a more promising annual power production if one assumes that the mast anemometer is the more accurate measurement tool for the real behaviour of the wind compared to the nacelle anemometer. Therefore, in this project, the av-

erage wind speed measurements will be taken from the mast anemometer in order to have as reliable result as possible.

### 3.3 Inspected turbine component

There are many factors that can impact the lifetime of a turbine and different components must be able to endure various conditions. For instance, the turbine's shaft must endure axial-and cyclic forces and be able to operate under frequently varying wind conditions [39]. A very important design criteria is choosing the right bearings to support and carry the main shaft loads. The direct drive turbine considered in this thesis has two spherical roller bearings both located on the main shaft. This type of bearing is most commonly used to support the main shaft due to its ability to accommodate misalignment between the shaft and the bearing housing. However, their serviceable lifetime are often much shorter than their designed lifetime. This is due to the fact that many of these bearings are experiencing damage from wear, which reduces the lifetime [40]. For this thesis, the lifetime of the main bearing was examined. The bearing lifetime indicates how long the bearing in question is expected to last. However, there are many factors that need to be taken into account, such as how the loads applied to the bearings fluctuate depending on wind conditions [41].

To compare if the expected performance of the wind turbine corresponds to its actual performance it was investigated whether the lifetime differed. Therefore, two sets of lifetime calculations were performed for the main bearing, one based on the simulated data and one based on the measured data.

### 3.4 Wind distribution

Since the turbine is affected by wind speed the first step was to compare the expected wind distribution to the actual wind distribution for the normal power production case over a one-year period.

Figure 11 shows the measured wind distribution, depicted in blue, and the simulated wind distribution, depicted in red.

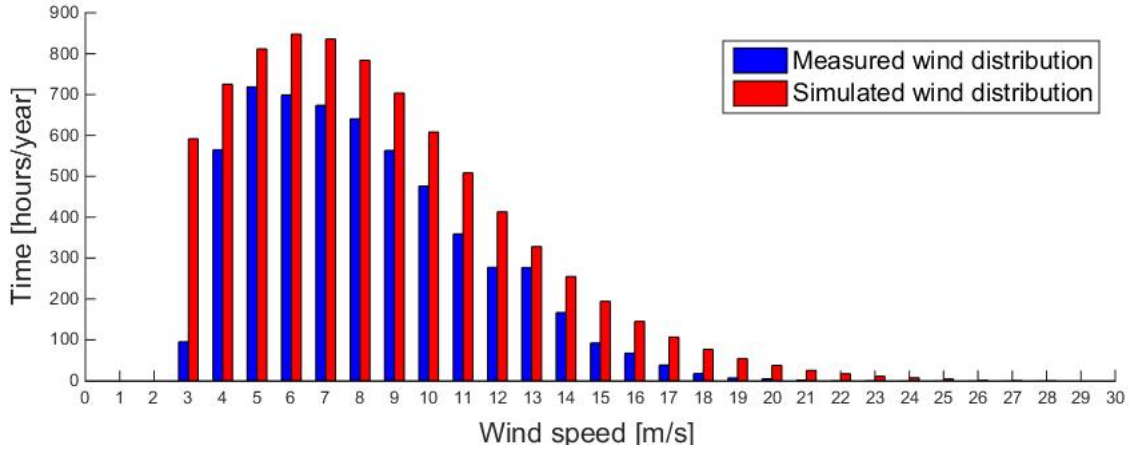


Figure 11: Measured-and simulated wind distribution for the normal power production load case

As can be seen in Figure 11, the total amount of hours for normal power production based on the simulated data is much longer compared to the when it is based on the measured data. The measurements were taken from the first year of production from a test turbine. It is therefore understandable that more faults occur during its initial period. It would therefore be interesting to make comparisons from a later stage of the turbine's lifetime. Unfortunately, the access to the measured data was only available for the turbine's first year of production and therefore no further analysis was made.

The figure illustrates how the simulated data set contains higher wind speeds compared to the measured data set, as in reality the wind did not reach as high speed as the simulations predicted. Therefore, following graphs will contain more data points for the simulated data sets compared to the measured ones.

Both the measured and the simulated wind distribution are based on site specific data obtained from a one-year measurement period. Therefore, it is assumed that the aforementioned differences between the data sets could be a result of the yearly deviation of wind speeds or that the simulated data is overestimating the wind speeds.

### 3.5 Evaluation of collective data

The measured data came from a one-year measurement programme that consisted of a number of sensors sending several signals every second about the functionality of the turbine as well as factors affecting the turbine. If every signal was to be analysed the amount of data would be tremendous. In order to limit the amount of collected data a decision was made to base the lifetime calculations on data files containing a 10-minute average data for the measured signals. Since the calculations were

based on normal power production all files containing a start-up, shut-down or emergency shut-downs were sorted out, together with files containing zero or a negative 10-minute average power production. Furthermore, only the files containing a 10-minute average wind speed above the cut-in wind speed and below the cut-out wind speed were considered for the calculations. The files were sorted based on their 10-minute average wind speed with a bin interval of 1 m/s. In other words, for an average wind speed of 5 m/s all files containing a 10-minute average wind speed of 4.5-5.5 m/s were included. Vectors were created based on this sorting method, which contained the average value of the desired signals for every wind speed.

The signals required in the lifetime calculation of the main bearing are the ones measuring the axial- and radial forces acting on the main bearing as well as the shaft's rotor speed.

There were no problems finding the aforementioned signals for the simulated data and the lifetime could be obtained relatively simply. However, for the measured data the signals measuring the forces acting on the main bearing were missing and the lifetime could therefore not be calculated directly. A decision was made to examine if a correlation could be found between the simulated axial- and radial forces to other simulated signals. The correlation could then be used for determining the values of the measured axial- and radial forces acting on the main bearing. It was decided to focus on the blade root bending moments in order to find a possible correlation. The decision was made because data from the blade root bending moments are available both in the measurement programme and in the simulated programme. Furthermore, the wind turbine consists of a chain of functional elements where the rotor is the first element. Therefore, the properties of the rotor has a decisive influence of the rest of the system in many aspects. The loads on the turbine blades are passed on to other components and can therefore determine their loading to a great extent [42].

Figure 12 shows the bending moments acting on the turbine blades along with the forces acting on the main bearing. The red lines on the blades indicate where the sensors were positioned.

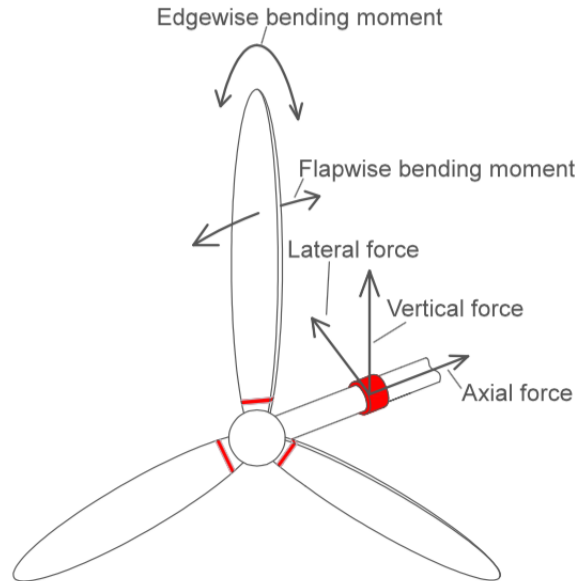


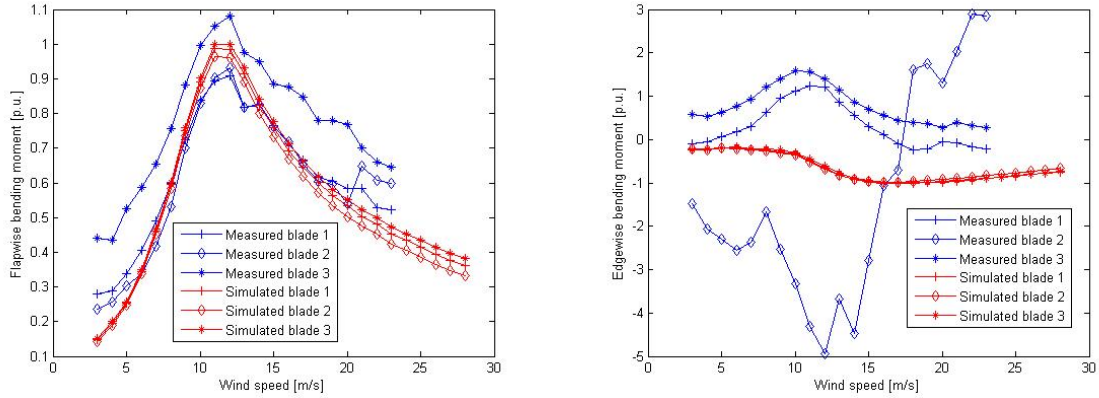
Figure 12: Bending moments acting on the turbine blades and forces acting on the main bearing

The radial force,  $F_r$ , is not illustrated in Figure 12. It is the resultant force of the vertical-and lateral forces acting on the main bearing as can be seen in Equation 6.

$$F_r = \sqrt{F_{lateral}^2 + F_{vertical}^2} \quad [N] \quad (6)$$

The sensors measuring the blade root bending moments were placed at different positions on the blade for the simulated-and measured signals. The sensors measuring the simulated signals were positioned on a few locations along the blade. The correlation between those positions were proven linear and therefore a linear interpolation of the simulated data was made to obtain the bending moments in a similar position to where the measured sensors were located.

Both the flapwise-and edgewise bending moments were extracted from the measured-and simulated data, the results are shown in Figure 13. Since the turbine blades are rotating, it was assumed that the 10-minute average bending moments acting on the blade root would be similar for all three of the blades. This was however not the case for the measured data, especially not for the measured edgewise bending moment as can be seen in the figure.



(a) Flapwise bending moment against wind speed      (b) Edgewise bending moment against wind speed

Figure 13: Simulated and measured flapwise bending moment (a), and edgewise bending moment (b)

Since the behaviour of the measured edgewise bending moment differ substantially between the three blades and also from the simulated bending moment, it was assumed that the measured signals were not accurate. Therefore, it was decided to only use the flapwise bending moment in order to find a correlation to the axial-and radial forces acting on the main bearing.

For the flapwise bending moment, Figure 13a, the measurements from Blade 3 deviate substantially from the the other values. It was therefore assumed that the signals from Blade 3 were not accurate enough. However, it was decided to proceed with the calculations based on both including and

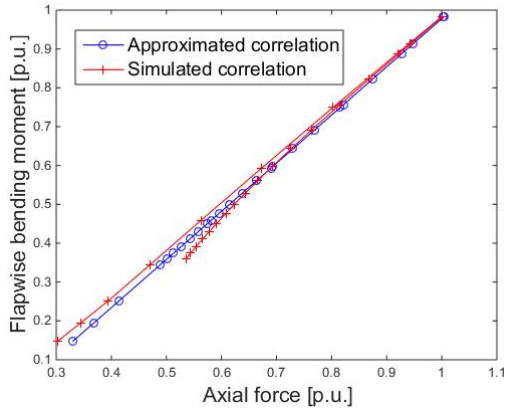


excluding Blade 3 in order to examine how much the deviations caused by Blade 3 would affect the calculated lifetime of the main bearing. The differences between the measured and simulated flapwise bending moments are quite big at higher wind speeds. A contributing factor to this might be that the highest wind speeds do not occur as frequently as lower wind speeds. Therefore, there are very few samples behind the measured data for the highest wind speed and a single sample can affect the result considerably. There is also quite some difference between the simulated and measured flapwise bending moments at low wind speeds as Figure 13a demonstrates. Low wind speeds were frequently occurring during this particular one-year period and therefore there is a lot of measurement data available for that range of wind speeds. A single sample at low wind speeds is therefore less prone to affect the average and thus this group of data is considered more reliable. Therefore, a possible explanation of the differences between the simulated and measured bending moments is that the simulation is underestimating the flapwise bending moment at low wind speeds.

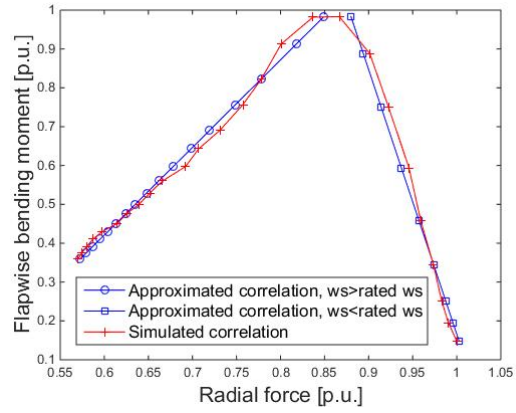
## 3.6 Correlation

Since the wind turbine has three blades it was questioned whether a single blade was enough to represent the correlation or if a combination of all three blades was a better option. Therefore, four correlations were examined, one was based on the average bending moment of all three blades and the others were based on Blade 1-3 individually. The correlation between the axial force and the flapwise bending moment was found by plotting the two simulated variables against each other and then a linear trend line of the outcome was constructed. The same was done for the radial force, but due to its behaviour two linear trend lines were used to approximate the outcome.

The result of the correlations based on the average flapwise bending moments on all three blades and the forces acting on the main bearing are demonstrated in Figure 14.



(a) Flapwise bending moment against axial force



(b) Flapwise bending moment against radial force

Figure 14: Correlation between the average flapwise bending moment of the three blades against the axial force (a), the radial force (b)

Similar graphs were constructed based on the three blades individually, and the equations for the linear relations were obtained. The results can be seen in Table 2. Note that the parameters in this table has been scaled according to the conditions stated in Chapter 1.3.

Table 2: Equations for the axial-and radial forces based on different flapwise bending moments

Based on flapwise bending moment from:	Axial force	Radial force, $V < \text{rated } V$	Radial force, $V > \text{rated } V$
Blade 1	$F_a = \frac{0.261 + M_{f,b1}}{7.881 * 10^6}$	$F_r = \frac{6.995 - M_{f,b1}}{4.333 * 10^7}$	$F_r = \frac{0.927 + M_{f,b1}}{1.430 * 10^7}$
Blade 2	$F_a = \frac{0.271 + M_{f,b2}}{7.768 * 10^6}$	$F_r = \frac{6.853 - M_{f,b2}}{4.246 * 10^7}$	$F_r = \frac{0.971 + M_{f,b2}}{1.445 * 10^7}$
Blade 3	$F_a = \frac{0.253 + M_{f,b3}}{7.945 * 10^6}$	$F_r = \frac{7.075 - M_{f,b3}}{4.382 * 10^7}$	$F_r = \frac{0.898 + M_{f,b3}}{1.419 * 10^7}$
Average of Blade 1-3	$F_a = \frac{0.261 + M_{f,avg}}{7.865 * 10^6}$	$F_r = \frac{6.974 - M_{f,avg}}{4.320 * 10^7}$	$F_r = \frac{0.932 + M_{f,avg}}{1.431 * 10^7}$

Where

$V$  = wind speed

$F_a$  = axial force acting on the main bearing

$F_r$  = radial force acting on the main bearing

$M_{f,avg}$  = average flapwise bending moment of the three blades

$M_{f,b1}$  = flapwise bending moment of Blade 1

$M_{f,b2}$  = flapwise bending moment of Blade 2

$M_{f,b3}$  = flapwise bending moment of Blade 3

As can be seen in Table 2, the constants in all four equations for the axial force are relatively similar. The same applies for the two different groups of equations for the radial force. The differences in the constants derives from the simulated flapwise bending moment being slightly different for the three blades, as illustrated earlier in Figure 13a. The figure also shows how the flapwise bending moment deviates even more between different blades when it is based on the measured data. It is therefore realised that the resulting forces will differ as well when based on the measured data from different blades. It is not clear though to how big extent these differences will affect the expected lifetime. The lifetime calculation was therefore proceeded based on all four sets of correlations individually.

By using the equations in Table 2, the axial-and radial forces were calculated based on the measured flapwise bending moment. The result can be seen in Figure 15 together with the forces obtained from the simulation. In the figure, M stands for the calculated forces based on the measured data, and S stands for the forces obtained from the simulated data.

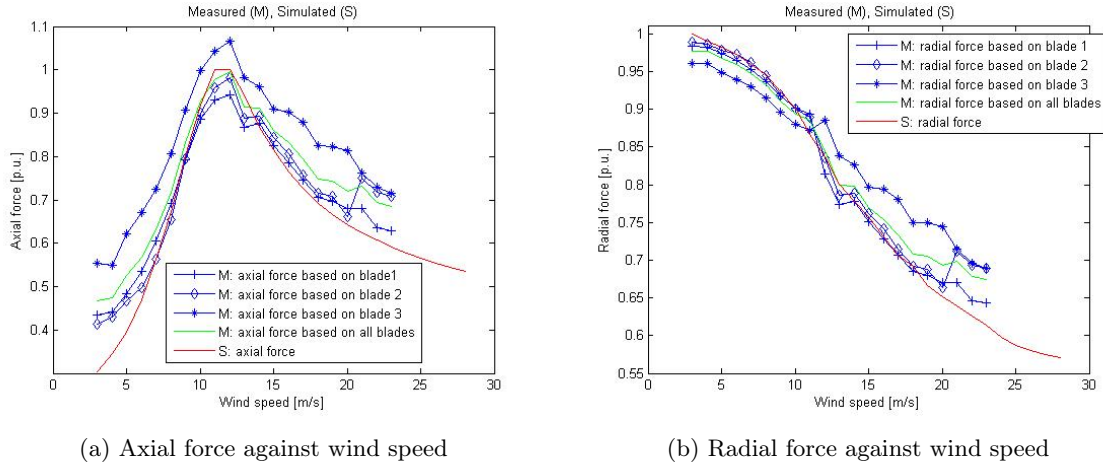


Figure 15: The axial (a) and radial (b) forces acting on the main bearing based on the simulated and the measured data

Figure 15 shows that the calculated axial-and radial forces are following a similar trend as the simulated forces. This means that the calculated forces are roughly the same as the simulated ones, as was expected. Figure 15a shows how the axial force increases with the wind speed until it reaches the rated wind speed. At the rated wind speed the blades begin to pitch. With a steeper blade pitch the smaller is the area of the blade that the wind is hitting and so the axial force decreases. It should also be mentioned that as the blades get pitched the power in the wind is not fully utilized. The power in

the wind increases with increased wind speeds but the turbine will suffer damages if it is operating for a long period of time at very high speeds. Therefore, by pitching the blades, a part of the power will be curtailed in order to protect the turbine.

The radial force acting on the main bearing is heavily influenced by the gravitational force. The weight of the hub and the weight of the three blades are key factors in this relation. Figure 15b shows how the radial force decreases with higher wind speeds. An hypotheses to why this behaviour occurs is that the turbine is lifted up by the wind and therefore the radial force decreases with higher wind speeds.

### 3.7 Lifetime calculations of the main bearing

A specific combination of the main bearing's axial-and radial forces, as shown in Equation 7, is called the dynamic equivalent force,  $P_d$ . It is the equivalent force acting on the main bearing and it is a function of time as it is dependent on wind speed and direction of the wind [43].

$$P_d = b_x F_r + b_y F_a \quad [N] \quad (7)$$

Where

$F_r$ = radial force [N]

$F_a$ = axial force [N]

$b_x, b_y$ = calculation factors for the specific spherical roller bearing type

If  $\frac{F_a}{F_r} \leq e$  then

$$b_x=1$$

$$b_y=2.5$$

If  $\frac{F_a}{F_r} > e$  then

$$b_x=0.67$$

$$b_y=3.7$$

Where

$$e=0.27$$

Figure 16a shows the relation between the dynamic equivalent force and the wind speed while Figure 16b shows the corresponding rotor speed of the shaft to its respective wind speed. These two variables are used for the main bearing's lifetime calculations. In this figure, M stands for the calculated forces based on the measured data, and S stands for the forces obtained from the simulated data.

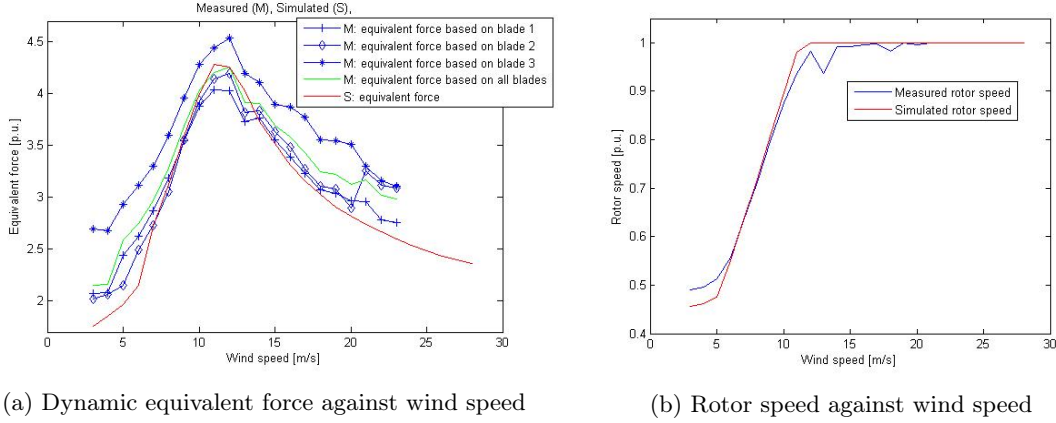


Figure 16: The dynamic equivalent force acting on the main bearing (a) and the rotational speed of the shaft (b)

By comparing Figure 16a to Figure 15a, one can see that the dynamic equivalent force is behaving quite similarly to the axial force when plotted against the wind speed. The reason why the dynamic equivalent force resembles the axial force so much instead of the radial force can be realised from Equation 7 where the constants relating to the axial force is much higher than the constants related to the radial force.

The rotor speed increases as the wind speed increases until the pitching of the blades occur. In theory, when the blades are pitched the rotor speed is supposed to stay constant, as illustrated by the simulated curve in Figure 16b. However, the measured data shows how the rotor speed deviates from its expected value when the blade is pitched. It is hard to say whether this behaviour takes place because of errors in the measurement programme or if the actual rotor speed was deviating at wind speeds above the rated wind speed.

The lifetime of the main bearing measured in years is calculated by using Equation 8 [44], [43].

$$L_n = \frac{a_1 a_2 a_3 \frac{10^6}{60n} \left( \frac{C}{P_d} \right)^p}{\text{hours/yr}} \quad [\text{years}] \quad (8)$$

Where

$n$  = rotating speed [ $\text{min}^{-1}$ ]

$a_i$  = life correction coefficient

$C$  = basic load rating, [N]

$P_d$  = dynamic equivalent force, [N]

$p = \frac{10}{3}$  for roller bearing

In this thesis, the  $a_1$  factor was set to 0.21 which corresponds to a 99% reliability of the main bearing surviving the estimated lifetime [41]. The  $a_2$  factor corresponds to the steel material used in the bearing. This factor is mostly historical and today it is almost always set equal to 1 [43]. The  $a_3$  factor is a condition factor and includes lubrication conditions and cleanliness among other things. The

factor is calculated using Equation 9 [43].

$$a_3(P_d) = \frac{0.1}{(1 - [\psi(3.39[1 - \frac{M}{\kappa^m}])^{\frac{5}{2}} \eta_c \frac{P_u}{P}]^w)^{\frac{c}{e}}} \quad (9)$$

Where

$\kappa$ = factor related to lubrication viscosity

$\eta_c$ =factor related to cleanness of the lubrication

$P_u$ =load limit, [N]

$\psi$ ,  $M$ ,  $m$ ,  $w$  and  $\frac{c}{e}$  are experimentally determined parameters

These factors and parameters are found in the SKF handbook relating to the specific spherical rolling bearing. The SKF handbook also gives the values for the basic load rating,  $P_u$  [45]. In this thesis work, the dynamic equivalent force is evaluated as a 10 minute average load. This will off course lead to a slightly less accurate result but was done in order to reduce the amount of data being used.

By using the lifetime equation, Equation 8, the lifetime was calculated for each wind speed and the results are shown in Figure 17. The figure is constructed in a way that the lifetime is stated in years for a constant value of the wind speed. For example, if the wind speed throughout the years would constantly be 5 m/s the lifetime based on measurements from Blade 3 would be around 50 years.

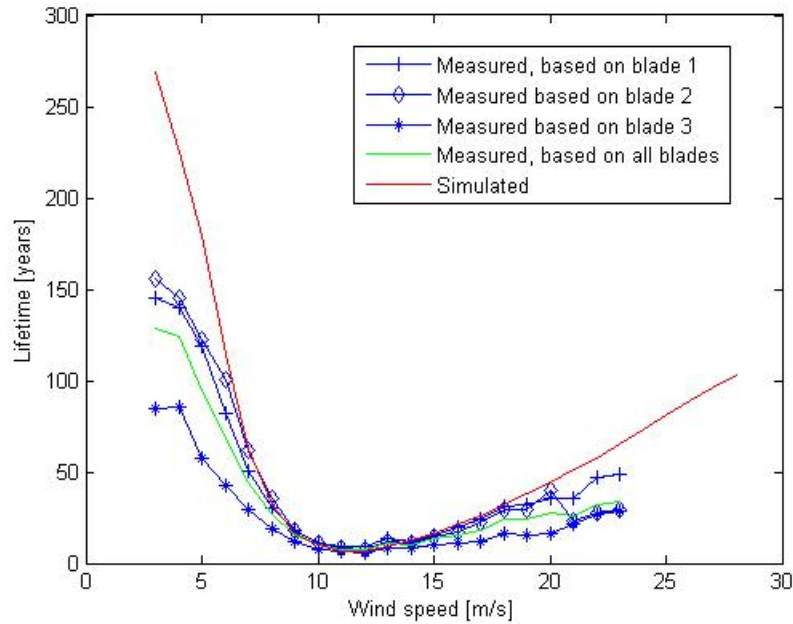


Figure 17: The lifetime of the main bearing for every wind speed based on the measured-and simulated data

Figure 17 shows that the lifetime of the main bearing is similar for the measured-and simulated data at medium high wind speeds. However, the lifetime differs a lot between the different data sets at low wind speeds. The lifetime is closely connected to the forces acting on the main bearing, as can be seen in Equation 8, the lifetime decreases as the forces increase. An explanation to this relation can partly be seen from Figure 15a where the axial forces acting on the main bearing for the measured case at low wind speeds are much higher than the axial forces for the simulated case. This difference between the two data sets explains the deviation in lifetime at lower wind speeds as shown in Figure 17. Furthermore, the higher the rotor speed is, the shorter the lifetime becomes. A low rotor speed in combination with a low equivalent dynamic force results in longer lifetime at low wind speeds. An interesting thing to notice in Figure 17 is that the lowest lifetime occurs during wind speeds around the rated wind speed, which raises the question how beneficial it is to operate the turbine at its rated wind speed if by doing so the lifetime shortens considerably.

The lifetime of the main bearing illustrated in Figure 17 shows the lifetime assuming a constant wind speed throughout the year. This is, of course, not the reality and to get a reliable number for the lifetime the wind speed's probability distribution in the case of normal power production needs to be included. Therefore, Equation 8 must be modified to include the variation in wind speed throughout the year. The lifetime equation for every wind speed was multiplied with its probability to occur,  $prob(ws)$ . A summation was then made over the equation to include all the wind speeds between the cut-in wind speed and the cut-out wind speed.

The modified lifetime equation is stated below.

$$L_n = \sum_{V=cut-in}^{V=cut-out} \frac{a_1 a_2 a_3 \frac{10^6}{60n(V)} \left( \frac{C}{P_d(V)} \right)^p}{hours/yr} prob(V) \quad [years] \quad (10)$$

The probability distribution for normal power production for the simulated case differs considerably from the measured case, which was illustrated in Figure 11. For the simulated case, the total number of hours the turbine is operating with normal power production is about 25% higher than the total number of hours for the measured case. This must be kept in mind while viewing the results of the lifetime of the main bearing. If the turbine would have been operating for more hours during that year the wear of the main bearing for the normal power production case might be different and therefore the lifetime would be different as well.

The lifetime of the main bearing for situations with normal power production is showed in Table 3. The lifetime is stated in years for a 99% reliability of the component reaching that lifetime.

Table 3: Lifetime estimations for different data sets

Based on:	Lifetime [years]
Blade 1 (measured data)	36.6
Blade 2 (measured data)	39.8
Blade 3 (measured data)	20.5
Average, Blade 1-3 (measured data)	31.0
Simulated data	79.0

Table 3 shows how the lifetime from the simulated data is much higher than the lifetime based on the measured data. This is probably due to the fact that for wind speeds lower than approximately 7 m/s, the lifetime is quite longer for the simulated data than the measured data, as Figure 17 shows. As can be recalled from Figure 11, wind speeds below 8 m/s occur for roughly half of the time throughout the year.

When comparing the lifetime based on the three blades, it can be seen that Blade 1 and Blade 2 have a relatively similar lifetime. However, when the lifetime is based on Blade 3 it gives a much shorter lifetime. That outcome was expected since the calculated radial and axial forces are much higher for Blade 3. However, the difference in the lifetime for Blade 3 compared to Blades 1 and 2 is that big that it seems like the measurements of the bending moment for Blade 3 is not accurate enough to base the lifetime calculations on. Therefore, it is assumed that the most accurate lifetime calculation are the ones based on Blade 1 and Blade 2, not the ones based on Blade 3 or the average of the three blades. Furthermore, if the bending moment measurements for Blade 3 would not have been so far off, it would have been expected that the average of the three blades would be the best indicator of the lifetime.



# 4 EVALUATION OF MEASUREMENTS

## 4.1 Accuracy of sensors

Wind turbines are closely monitored by multiple sensors that are placed at different parts on the turbine. The sensors are an essential part of keeping the turbine up and running as they give a good assessment of how the turbine is behaving during different conditions. By studying the signals, the chances of understanding the turbines different functions and perhaps preventing possible problems are increased. However, one must keep in mind that the signals do not always give a complete accurate account on the turbine's functions and that a certain scepticism over the measurements must be placed at all times. This thesis was a good example of a case when some signals were not behaving as they should during certain periods of time as well as some of the sensors were completely unreliable. There are many reasons as to why the sensors are not performing as they should. The sensors are sensitive to factors, such as what kind of glue is used to fix it to the turbine and how the glue is maintaining its properties. Furthermore, other possible reasons can be that the sensors are incorrectly mounted or the measuring devices inaccurately calibrated [46].

The following sub-chapter describes how the problem of unreliable sensors was tackled and to how big extent they are expected to have influenced the outcome.

## 4.2 Comparisons between signals for different time periods

Since the strain gauge sensors measuring the bending moments of the blades are very sensitive, it was desired to find time periods in which the signals seemed reliable. The 10-minute average of the flapwise bending moments were plotted over a long period of time to visualize its behaviour, which is demonstrated in Figure 18. The 10-minute average bending moments are assumed to be similar for the three blades since the blades are rotating. By taking this into consideration, shorter time periods in which the bending moments of the three blades were similar and no peaks occurred were detected and chosen for further examination. The measurements from those time periods were considered reliable and they are indicated by the red boxes in Figure 18. It was not enough to base the measurement solely on the longer of the two periods. This is because the highest measured wind speeds were only present in the shorter detected period, therefore data from both periods were combined.

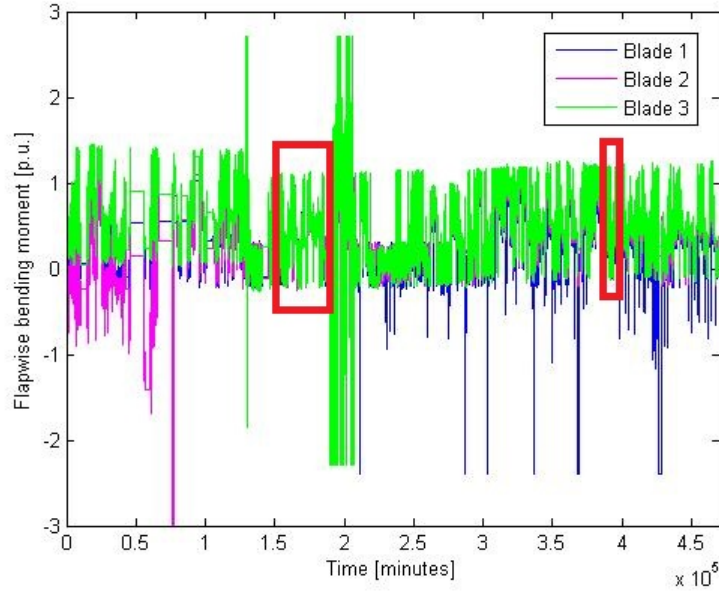


Figure 18: The 10-minute average flap wise bending moment with reliable measurement periods indicated by the red rectangles

The measured flapwise bending moment from the two reliable periods was plotted against the wind speed. It was compared to the flapwise bending moment obtained from both the full year measurement and from the simulated data as Figure 19 shows. In this figure, the measured data obtained from the full year is labelled M, the measured data from the shorter more reliable periods is labelled PM and the simulated data is labelled S.

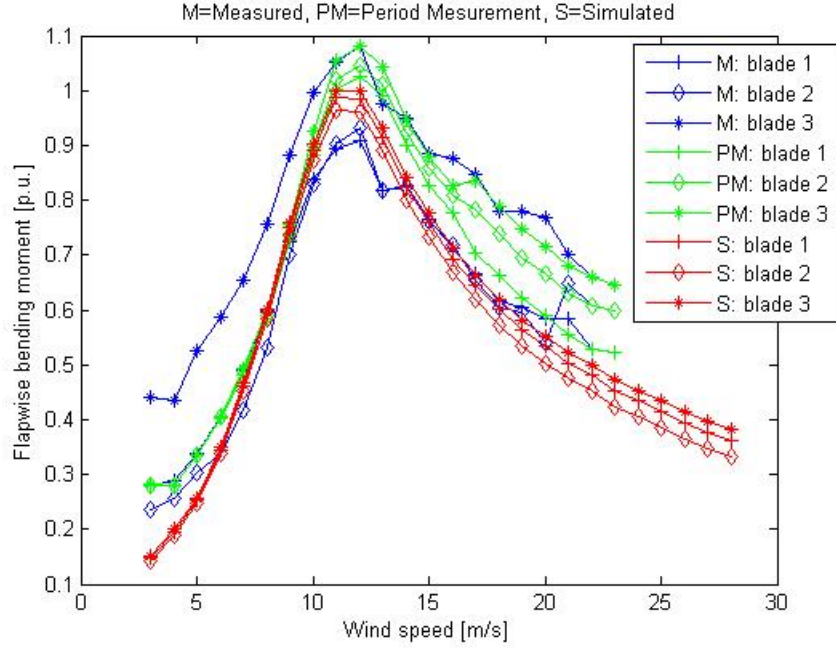


Figure 19: The 10-minute average flapwise bending moment against wind speed based on the reliable period, the full year period and the simulated data

The figure illustrates how the measured data extracted from the reliable period has a more similar trend to the simulated data. Furthermore, the bending moments of the three blades are more similar to each other for the shorter period compared to the full year measurement. What is also interesting in this figure is that for wind speeds around 7-10 m/s, the simulated data is very similar to the data extracted in the reliable period. However, for the highest wind speeds the differences are still significant as the measured data for the highest wind speeds are based on very few samples. Another thing that can be noticed in Figure 19 is that for wind speeds under 10 m/s, the measurements from Blade 1 seem very reliable even for the full year period as it roughly follows the same data points as the reliable period.

The lifetime of the main bearing based on the data from the measured reliable period was calculated in the same way as the lifetime calculations based on the measured data for the full year period. Only the flapwise bending moment was extracted from the reliable period while the rotor speed and wind distribution were still based on the data from the one year measurement. These decisions were made because the rotor speed and the wind speed are considered as less sensitive measurements. The lifetime for every wind speed based on the reliable period, the full year period and the simulated data are shown in Figure 20.

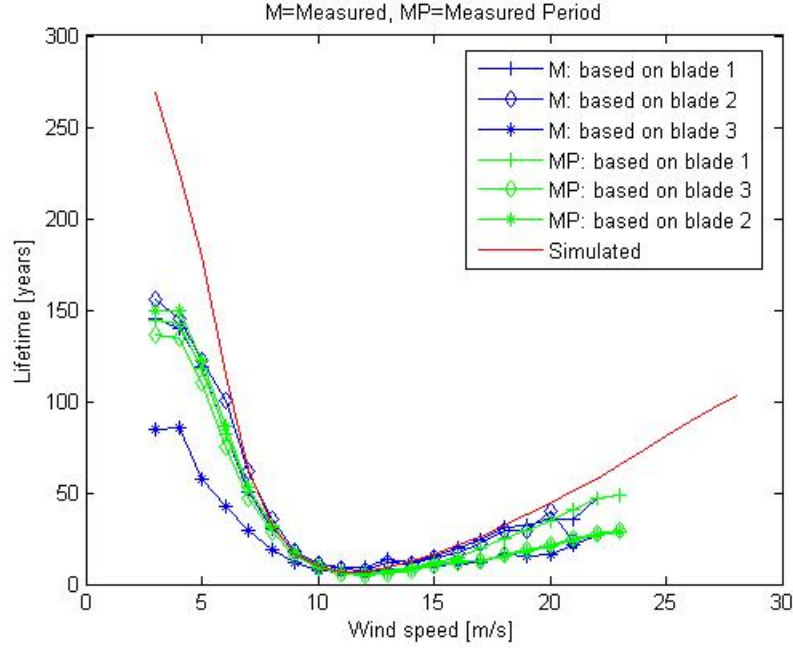


Figure 20: The lifetime of the main bearing for every wind speed based on the reliable period, the full year period and the simulated data

The definite lifetime of the reliable period, by taking into account the probability of each wind speed occurring throughout the year, was obtained in the same way as the lifetime based on the full year measurement. The result is demonstrated in Table 4 together with the definitive lifetime of both the full year period and the simulated data.

Table 4: Lifetime estimations based on the reliable period, the full year period and the simulated data

Based on:	Lifetime [years], (measured data)	Lifetime [years], (period measured data)
Blade 1	36.6	36.4
Blade 2	39.8	33.4
Blade 3	20.5	37.3
Average, Blade 1-3	31.0	35.7
Simulated data	79.0	79.0

The table shows how the lifetimes based on the data obtained from the reliable measured period are much more similar for each case compared to the lifetimes based on the full year measurements. Furthermore, it seems like the full year measurements from Blade 1 are relatively dependable since it gives a similar lifetime as the one from the reliable period for Blade 1. This derives from the fact that the majority of the wind speed distribution throughout the year is under 10 m/s, as Figure 11 shows, and at these wind speeds the measurements from Blade 1 seem accurate.

According to the IEC 61400 standard, which states turbine's design requirements, the lifetime of the bearing must be at least 20 years based on a 90% survival reliability [25]. The calculations performed in this project are based on a 99% reliability, and even though the lifetime of the simulated data is more than twice as high as the measured data, the lifetime based on the measured data still follows the recommendation with a high marginal. However, what needs to be kept in mind is that these calculations are only based on the situation with normal power production and therefore the result is likely to change if all the other design load cases were to be included.

## 5 INTERVIEWS WITH TURBINE OWNERS

After having done the lifetime calculations based on sensor measurements for the real life data and for the simulated data, the question arose as to whether the owners of wind turbines could do similar calculations. It was of interest to find out what kind of information the manufacturer is willing to give access to and whether that information differed between owners. In addition, questions were asked regarding how their maintenance schedule was constructed and if the schedule would change if the owner had access to further information.

Interviews with five different turbine owners were conducted. The owners differed a lot in the size of their business, the biggest owner has around 6000 MW of installed capacity while the smallest owner has around 35 MW. It was therefore interesting to find out if the bigger companies had more access to information relating to the design of the turbine than the smaller ones, if they could influence the negotiations with the manufacturer to a greater extent.

All of the owners have turbines from different manufacturers and they all agreed that it was hard to get an access to documents stating the design of the turbine from them. It differed a bit between manufacturers how willing they were to share information but it appeared that all of them were quite strict on giving added access to documents if it was not stated in the original agreement. One of the owner expressed his surprise on how the manufacturer treats the owner and the secrecy that is surrounding the manufacturers operation. That person had previously worked in the gas turbine business and said that the lack of information flow between different actors was unique in the wind turbine industry. All of the owners however understand the reluctance of the manufacturer of disclosing information containing the design of a turbine. The manufacturing business is a competitive one and the manufacturers are afraid of confidential information getting into the wrong hands.

All of the owners agreed that they were interested in receiving documents stating the design of the turbine as well as receiving information on how the dynamic simulations were constructed. They all said that it would be very good to have an access to it though some were unsure if they would actually use that information. One of the bigger owner stated that when choosing between different manufacturers they tend to choose to conduct business with the one disclosing more information about the design of the turbine. Those documents could reduce the investment risk. They have previously decided not to proceed with buying a turbine as they felt that there were too many potential risks associated with the turbine. However, that same owner said that if they would have gotten more information about the turbine and its performance they perhaps would have made another decision. Another owner however stated that even though a manufacturer would be willing to share some of the documents, the owner is mostly focused on what kind of turbine he is buying and how that turbine is performing. That owner will choose the most profitable turbine and accept that they do not get all the documentation that they would have liked.

One of the smaller owner explained that they did not even ask in the negotiating phase for the design documentation and the simulations. The main reason to why they are disinterested in these documents is their lack of human resources to look into these documentations and the fact that it is a

small business operating few turbines. However, for the larger companies their attitude was different. Some of the owners had actively been trying to get access to the documentations for a long time but to no avail. One owner stated that every time they have a new project starting they invite different manufacturers to place a bid on the project. This tactic can result in the manufacturer being willing to disclose some information that he was previously reluctant to do in a bid to sign a deal with the owner. Only one owner, a medium big owner, got access to documents which included the complete load calculations and the all the simulations. However, they only got these documents from one of the manufacturers as the others denied their request. The owners all agreed that it would perhaps be possible to receive more information about the design of the turbine in the negotiating phase when the manufacturers are competing with each other or before the final payment if it is stated in the contract that they should disclose the information. However, if they had not received the information after those two occasions then it is almost impossible to require them afterwards.

All of the owners expressed their interest in getting more information containing how the turbine is designed to perform at different operating conditions. When asked how they know that their turbines are working as they were designed to, most of the owners mention the power curve and the SCADA (Supervisory Control And Data Acquisition) system. The power curve, which states how much power should be produced at each wind speed, is used for comparison purposes as they check if the turbine is following the curve. The SCADA system is used to track signal measurements and failures of components. If the availability of the turbine is not as expected, they conduct analysis to figure out what is driving the availability down. Some owners compare how similar turbines in different locations are operating and try to find similarities and differences when a failure occurs. Many explain that they use the condition monitoring system, CMS, which monitors the condition of different components. The owners want to further understand how the turbine operates and how it is supposed to perform. One owner was especially interested as the company had been in project phase for many years but now wanted to focus on their existing turbines. They wanted to use the information to make a better maintenance plan, go from a time based maintenance to a preventive maintenance.

No owner had access to lifetime calculations on turbine components that were based on simulated data. They were doubtful that they would get access to how the manufacturer performed the simulations. However, some owners thought that in the turbine purchase phase they could be invited to some kind of a presentation where the manufacturer could explain in further detail how the calculations for a certain component were performed. All of the owners agreed that there was no guarantee that a turbine would operate for 20 years, they just have to put their faith in the manufacturer. The manufacturer makes simulations and calculations and states that the turbine should work for 20 years. The owners want to have a second opinion on these calculations and therefore an unbiased third party goes over the accuracy of the lifetime calculations. Some owners said that the only way to guarantee the lifetime is to have a full inclusive service agreement with the manufacturer for 20 years. By doing so, the owner trust that the manufacturer believes in their own design otherwise the manufacturer would not take the risk of having to have to repair it so often. However, this lifetime agreement is very expensive.

The owners did not know in detail how specific wind speeds influence the wear of the turbine. They only know in general that turbulence conditions affect the turbine as well as high winds and frequent starts and stops of the turbine. It was easy for them to answer yes when asked if they were interested in gaining information about the relation between wear and wind speeds. However, it was harder to decide if they would use that information to operate the turbine in a different way. Some owners said it was unlikely that they would operate any differently. They know under which wind class their turbine is and they would monitor the turbine to analyse the failure rate while also having an unscheduled

maintenance programme. Some owners would like to use that information for preventive measures for their maintenance and operation. One owner said that it would be straightforward saying yes if that meant that by curtailing wind they would get a longer lifetime. It would be simple to see if that would be profitable, by curtailing certain quantity some money will be lost but they would gain a certain lifetime which would save specific amount of money. However, if that would mean that it would cost much money or take much effort then probably they would not operate the turbine differently.

Normally the manufacturer will give an access to around 20-50 signal measurements out of maybe 2000. The signals can vary in resolution and the manufacturer can insist on charging the owner more money for a higher resolution signals while some will not even give them that opportunity. The measured data is used proactive to minimize the downtime of the turbine as well as it helps them understand why a certain component is failing at a higher rate than was expected. Added access to signals can be reached by, for example, installing a CMS system. However, a turbine is normally under warranty for the first two to five years. If the owner wants to use an additional measurement system, like the CMS, the warranty will not apply as then the manufacturer will say that the implementation of the system is influencing their own system and they can not be held responsible. Therefore, the owner is more or less forced to wait for the warranty to end before they install the new system to gain additional signals.

The maintenance schedule differed considerably between the different owners. Some owners outsourced its whole O&M (Operation & Maintenance) schedule to the manufacturer by having a 20-year service agreement with the manufacturer. The main reason for that decision was that the manufacturer knows the turbine design best and the owner wants them to have more responsibility and investment in the turbine. Normally when buying a turbine there is a two to five-year service warranty from the manufacturer. One owner said after that period, they usually decide to use in-house maintenance for the bigger sites or even use a third party if they think the manufacturer is too expensive. For smaller maintenance an in-house team is used but for larger failures they rely on outsider's maintenance team. In those situations, it is most common to use the manufacturers maintenance team as they maybe did not give all the information concerning the turbine during the purchase. Therefore, they could have a more detailed instruction on how to fix the failure.

Another owner said that they sometimes outsource some technicians but not many whole projects. The O&M schedule depends a bit on the location of the turbines, if there are few turbines at a site far away it might be profitable to outsource the service. For bigger sites with many turbines it is common to have its own in-house team working on the maintenance. Some owners use a so called base agreement for their turbines, a scheduled service twice a year. If an unexpected occurrence happens they will have to call for extra maintenance.

Many owners try to have a preventive maintenance but it is hard to predict when it is needed. They try to look into the CMS but they are maybe not using it as much as they could. Some owners have their own technicians constantly checking the condition of the turbines to see in advance if a fault occurs. One owner states that when they see a failure occur in the CMS they will try to understand the root cause and at what pace the failure will affect other components in the turbine. If they see a serial defect on some component they can start to do some preventive maintenance or try to delay the failure and start to replace the components in different turbines proactively before they fail. When they can see in advance that a component is failing they can decide on how to exhaust the component in the most optimal manner. They could choose to replace it during summer when the wind is less, the electricity price is low or when the company has enough capacity. The owner say they have a rather good indicator as to how long each failure will take until a total breakdown of the component occurs. The owners all have turbines from different manufacturers and not enough turbines of the



same type. Therefore, comparative analysis and planning a preventive maintenance can be very hard.

When asked if they would like to have more in-house O&M the smaller owners were less enthusiastic than the bigger ones. The smaller owners did not think it would be beneficial for so few turbines to have their own in-house team and therefore they buy a support from other companies, even though they expressed their desire to be more in control over their turbines. Many of the owners agreed that by having access to the design documentation and simulations there would be a better possibility of using to a greater extent in-house O&M. Some would consider to out-source it to a third party if they could see that they could profit from it. One owner is actually offering other turbine owners their O&M service as the owner has sufficient knowledge and competence to do service and maintenance themselves. However, they do not have any more information or documents about those turbines than their owners.

One owner said that sometimes it is not necessary for them to get a longer lifetime of a component as they want to repower a site. That is, they will take down a smaller turbine and replace it with a bigger one. It can be beneficial for them to take down smaller turbines and sell them to Italy or Ireland as the smaller turbines will lead to higher subsidiaries in those countries. By selling the small turbines, the owner will gain some revenue and also they can reuse their permit for building bigger turbines at the same site and gain more power. In this case the lifetime of the turbine is not that important, the important thing is to find the most optimal time to decommission the turbines.

Only one owner mentioned that they have started to do similar studies as in this thesis for some bearings in older turbines as well as for some other components. They want to see if they can see a difference in how heavily the turbines have been loaded over the years and to find out if there is a difference to their expected lifetime compared to their actual one.

The owner can ask the manufacturer before and after they offer an upgrade to calculate the lifetime under certain site conditions and under upgraded conditions to see how the expected lifetime changes if they decide to operate the turbine “harder”. However, the owner has to ask the manufacturer to calculate the lifetime as they do not have the tools or sufficient information to do that themselves. Those calculations can help approximate for how long the owner can use the components in question. The components are expected to fail about 10% over 20 years so they want to know that if they operate the turbine for maybe 25 years, how much more will the main components fail during those extra years of operation. They want to know if they can expect to extend the lifetime of the turbine beyond year 20. Only some manufacturers offer these services. Manufacturers that are quite big and that the owner has a big business with help them with these investigations of the bearing lifetimes. However, the smaller manufacturers and the ones that do not have a big business with the owner think that these investigations are too expensive or they think that these are confidential information which they are afraid that their competitors can take advantage of. The owner has started to try to understand by looking at operational data how the bearing and its lifetime is affected at different conditions, what the difference is between bearings which have been loaded differently for different turbines. However, they do not have any sensors placed on the bearing nor on the blades to measure the forces and moments. It would be interesting to know how they measure these parameters but no further information was gained from the owner.

# 6 CLOSURE

## 6.1 Discussion & Conclusion

The main findings from this project are that there are great differences in the lifetime estimations depending on if its based on the simulated-or measured data of the turbine. Furthermore, it was concluded that the simulations of the wind turbine could be used to find correlations between different signals. However, it seems like the turbine owners do not have enough access to information in order to perform lifetime calculations in a similar way as was done in this project.

The results from the calculations in this project do not give a full picture of the lifetime of the main bearing since only the normal power production case was taken into account. The thesis rather shows a method of how to analyse the lifetime of a bearing and it examines differences between the expected and the actual performance of a wind turbine. In this project the 10-minute average data was used to estimate the lifetime of the component. It would of course give a more accurate estimate if data from a shorter time period were used.

Even though a lot of access to private documents was granted for this thesis, it was at times hard to use the data. In many cases, the source of the data was not sufficiently explained, such as from what part of the turbine the signals were coming and what some sensors were actually measuring. These issues had quite an impact on the work process as it made the project quite more complicated than initially expected. In addition, there are some shortcomings in the data files, as around 15 days worth of data is missing as well as some signals are not present at every time interval. Therefore, one must be careful when assessing the results as inaccurate data can influence the outcomes. Furthermore, it is very important to verify the measured data as the sensors do sometimes not give accurate measurements during some periods, as was the case in this thesis. Therefore, basing calculations or predictions on measured data without confirming its reliability can have a big impact on the result.

It would be very useful if a single blade could represent a correlation to the forces acting on the main bearing because then lifetime calculations could be done even though sensors of all three blades were not working at the same time. However, one must be careful when trusting the measurements from the blades. One way to verify if the measured signals from a single blade is accurate is to compare it to measurements from another blade. Therefore, its preferable if the sensors for at least two blades are operating at the same time or if the reliability of the signals from a single blade can be verified in some other way in order to calculate the lifetime based on a single blade.

As a result from the interviews, it seems like the owners of the turbines are unable to perform lifetime calculations based on the expected performance. This is due to the fact that they are not getting enough information about their turbines from the manufacturer. Since they do not get access to the simulation, they are unable to find correlations to other signals as done in this project. They could however, get an estimate of the lifetime of the main bearing based on measured data. This comes with the constraint that they have to install sensors measuring the forces on the main bearing and have measurements for the rotational speed of the rotor. Furthermore, it was concluded in the interviews that all of the turbine owners were interested in obtaining more information regarding the expected

performance of their wind turbines. However, only a few of them thought that they would actually use this information.

## 6.2 Future work

In this project a direct drive wind turbine was investigated. It would however be useful to perform similar calculations on geared turbines, as typically high speed shaft bearings and geared teeth in the gearboxes are very prone to fail and cause long downtimes. It would be preferable if the lifetime of the bearings could be continuously monitored. In that way, one could realise how the wear of the component is at each moment and calculations on the expected remaining lifetime could be performed. In addition, comparisons to other turbines and other periods of time could be made.

There is a lot of work to be done in the field of line relating to this thesis work. It would be useful to make similar lifetime calculations for other turbine components. By doing so, one will understand better how different factors affect the lifetime and perhaps develop new and better ways of operating and maintaining the turbine. An example of this is illustrated in Figure 17 where the highest wear of the main bearing seems to occur at wind speeds close to the rated wind speed. It would therefore be interesting to find where the highest wear of other turbine components occurs. If the highest wear for those components takes place in the same wind range, one could discuss the profitability of stopping the wind turbine during those wind speeds. That decision could be practical if a lot of lifetime would be spared and if the electricity prices are low during the times when those particular wind speeds are occurring. However, of course one has to consider the effect the frequent shut-downs has on the turbine, if that would in return wear some other components out more. Further studies in lifetime calculations of different components and increased analysis of signal outputs could make it easier to improve a turbine's maintenance schedule and even shift more to a preventive maintenance schedule compared to a only time based one.

The decision to change from an existing regime to another one is largely based on how much the transition will cost. There will, for example, be an added cost by installing more sensors on the turbines for increased measurements possibilities but the investment must be put into perspective of possible gains. By having a better measurement system and a team of analysts the gain in production time that can be reached by replacing parts before they break down can be worthwhile.

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# References

- [1] Runyon, J. *Illustrated History of Wind Power Development*. 2014. URL: <http://www.renewableenergyworld.com/articles/2014/04/global-wind-market-is-just-fine-thank-you.html> (visited on 02/04/2016).
- [2] WWEA. *World Wind Energy Report 2014*. Tech. rep. World Wind Energy Association, 2015.
- [3] Barnard, M. *Wind Energy: A Mature Buisness Challenging Fossil Generation Profits*. 2014. URL: [http://www.energyandpolicy.org/wind\\_energy\\_profitable\\_business](http://www.energyandpolicy.org/wind_energy_profitable_business) (visited on 02/04/2016).
- [4] Markovitz, V. "Sizing Up Wind Energy: Bigger Means Greener, Study Says". In: *National Geographic* (2012).
- [5] Haluzan, N. *Offshore wind power-Advantages and disadvantages*. 2012. URL: [http://www.renewables-info.com/drawbacks\\_and\\_benefits/offshore\\_wind\\_power\\_%E2%80%93advantages\\_and\\_disadvantages.html](http://www.renewables-info.com/drawbacks_and_benefits/offshore_wind_power_%E2%80%93advantages_and_disadvantages.html) (visited on 02/08/2016).
- [6] Burgess, J. *The Future of the Wind Industry*. 2012. URL: <http://oilprice.com/Latest-Energy-News/World-News/Global-Wind-Energy-Outlook-The-Future-of-the-Wind-Industry.html> (visited on 02/08/2016).
- [7] Barett, J.T. "Horizontal Vs. Vertical Wind Turbines". In: *Demand Media* (n/a).
- [8] Dvorak, P. *Why not more vertical-axis wind turbines?* 2014. URL: <http://www.windpowerengineering.com/design/vertical-axis-wind-turbines/> (visited on 05/11/2016).
- [9] Carlson, O. *Lecture notes in Sustainable Power Production and Transportation*. Chalmers University of Technology. 2015.
- [10] AWS Scientific, Inc. *Wind Resource Assessment Handbook. Fundamentals for conducting a successful monitoring program*. 1997.
- [11] Gipe, P. *Wind Power. Renewable Energy or Home, Farm and Business*. Chelsea Green Publishing Company, 2014.
- [12] Watson, D. E. *Wind Turbine Power Coefficient (Cp)*. 2015. URL: <http://www.ftexploring.com/wind-energy/wind-power-coefficient.htm> (visited on 02/25/2016).
- [13] Gurit. *Wind Energy Handbook, Wind Turbine Blade Aerodynamics*. n/a. URL: <http://www.gurit.com/wind-energy-handbook.aspx> (visited on 04/20/2016).
- [14] Chen, B. *Pitch-regulated and Stall-regulated Wind Turbine*. 2013. URL: <http://www.bindichen.co.uk/post/Fundamentals/Pitch-regulated-and-Stall-regulated-Wind-Turbine.html> (visited on 03/15/2016).
- [15] Association, Danish Wind Industry. *Power Control of Wind Turbines*. 2003. URL: <http://xn--drmrre-64ad.dk/wp-content/wind/miller/windpower%20web/en/tour/wtrb/powerreg.htm> (visited on 03/14/2016).
- [16] N/a. *Swept Area and Rated Power*. 2010. URL: <http://www.power-talk.net/swept-area.html> (visited on 03/16/2016).
- [17] Morris, L. *Direct Drive vs. Gearbox: Progress on Both Fronts*. 2011. URL: <http://www.power-eng.com/articles/print/volume-115/issue-3/features/direct-drive-vs-gearbox-progress-on-both-fronts.html> (visited on 03/18/2016).
- [18] Busby, R. L. *Wind Power, The Industry Grows Up*. PennWell Corporation, 2012.
- [19] Engineering, Learn. *Wind Turbine Design*. 2013. URL: <http://www.learnengineering.org/2013/08/Wind-Turbine-Design.html> (visited on 04/22/2016).
- [20] Jamieson, P. *Innovation in Wind Turbine Design*. John Wiley Sons, Ltd, 2011.

- [21] Ragheb, M. and Ragheb, A. M. *Wind Turbines Theory - The Betz Equation and Optimal Rotor Tip Speed Ratio*. Tech. rep. Department of Nuclear, Plasma and Radiological Engineering, Department of Aerospace Engineering, 2011.
- [22] Weir, J. Twidell T. *Renewable Energy Resources*. 2nd. Taylor Francis Group, 2006.
- [23] Ahmed, S. *Wind Energy: Theory and Practise*. 3rd. Asoke K. Ghosh, Oct. 2015.
- [24] Engineering, IHS. *Blades (wind turbine) Information*. n/a. URL: [http://www.globalspec.com/learnmore/electrical\\_electronic\\_components/power\\_generation\\_storage/alternative\\_power\\_generators/blades\\_wind\\_turbine](http://www.globalspec.com/learnmore/electrical_electronic_components/power_generation_storage/alternative_power_generators/blades_wind_turbine) (visited on 04/20/2016).
- [25] Svenska-Elektriska-Kommissionen. *Wind turbines Part 1: Design requirements*. IEC. 2006.
- [26] Veers, P. S. and Butterfield, S. *Extreme Load Estimation for Wind Turbines: Issues and Opportunities for Improved Practice*. Tech. rep. Sandia National Laboratories, 2001.
- [27] Research, Community and CORDIS, Development Service. *RELIAWIND Report Summary*. 2013. URL: [http://cordis.europa.eu/result/rcn/55560\\_en.html](http://cordis.europa.eu/result/rcn/55560_en.html) (visited on 02/04/2015).
- [28] Wilkinson, M. *Measuring Wind Turbine Reliability - Results of the Reliawind Project*. Tech. rep. GL Gerrad Hassan, 2011.
- [29] Nelson, G. *Establishing an In-House Wind Maintenance Program*. Tech. rep. Second edition. U.S. Department of Energy, 2011.
- [30] Institute, Swedish Standards. *Maintenance Terminology*. IEC 13306. 2010.
- [31] Bangalore, P. *Load and Risk Based Maintenance of Wind Turbines*. Chalmers University of Technology. 2014.
- [32] Tjernberg, L. Bertling and Wennerhag, P. *Wind turbine operation and maintenance, Survey of the Development and Research Needs*. Tech. rep. Elforsk report 12:41, 2012.
- [33] Ahlström, A. *Aeroelastic Simulation of Wind Turbine Dynamics*. Tech. rep. Royal Institute of Technology, 2005.
- [34] Große, M. *Wind Measurement for Accurate Energy Predictions-An Overview*. URL: [http://www.wwindea.org/technology/ch02/en/2\\_2\\_1.html](http://www.wwindea.org/technology/ch02/en/2_2_1.html) (visited on 02/19/2016).
- [35] Moore, K.E., Bailey, B.H., and Bernadett, D. *Observed rotor-plane wind profiles derived from sodar measurements: Potential impact on turbine power performance*. Tech. rep. AWS Truewind, 2006.
- [36] Allik, A., Uiga, J., and Annuk, A. *Deviations between wind speed data measured with nacelle-mounted anemometers on small wind turbines and anemometers mounted on measuring masts*. Tech. rep. Institute of Technology, Estonian University of Life Sciences, 2014.
- [37] Wagenaar, J.W. and Davoust, S. *Use of a nacelle LiDAR to assess nacelle transfer functions following maintenance operations*. Tech. rep. EWEA, 2014.
- [38] Smith, B. et al. *Applicability of Nacelle Anemometer Measurements for Use in Turbine Power Performance Tests*. Tech. rep. National Renewable Energy Laboratory, 2002.
- [39] WMI. *Operational and Maintenance Costs for Wind Turbines*. n/a. URL: <http://www.windmeasurementinternational.com/wind-turbines/om-turbines.php> (visited on 03/16/2016).
- [40] Kotzalas, M. N. and Doll, G. L. "Tribological Advancements for Reliable Wind Turbine Performance". In: *Philosophical Transactions: Mathematical, Physical and Engineering Sciences* 368 (2010), pp. 4829–4850.
- [41] n/a. *Ball Bearing Load Ratings and Life Calculations*. 2014. URL: <http://www.nmbtc.com/bearings/engineering/load-life/> (visited on 03/22/2016).
- [42] Hau, E. *Wind Turbines, Fundamentals, Technologies, Application, Economics*. 3rd. Springer, 2013.
- [43] Harris, T. A. *Roller Bearing Analysis*. 4th. Wiley, 2001.
- [44] Yagi, S. and Ninoyu, N. *Technical Trends in Wind Turbine Bearings*. Tech. rep. NTN Technical Review No.76, 2008.

- [45] n/a. *SKF huvudkatalog*. Stamperia Artistica Nazionale, 1997.
- [46] Réthoré, P.-E. et al. “Systematic wind farm measurement data reinforcement tool for wake model calibration”. In: *Systematic wind farm measurement data reinforcement tool for wake model calibration*. 2009.