

Maintenance management of wind power systems
Cost effect analysis of condition monitoring systems

Master Thesis
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Abstract

The wind power industry has experienced a large growth the past years. The growth mainly focus on a growing market, better economical conditions for wind power because of political decisions and the development of large wind turbines and offshore farms. A goal is to increase reliability for turbines. The topic is even more important for offshore farms where service is difficult and expensive.

The answer for the wind power industry, for better maintenance management and increased reliability, could be Condition Monitoring Systems (CMS). Such systems are commonly used in other industries. They continuously monitor the performance of the wind turbine parts e.g. generator, gearbox and transformer, and help determine the best time for a specific maintenance work. How these systems could support the wind power user is investigated in this report.

The further step could be to implement CMS as a part of Reliability Centered Maintenance (RCM). RCM is a structured approach that focus on reliability aspects when determining maintenance plans, that is to find a balance between preventive- and corrective maintenance. Preventive maintenance is maintenance carried out before failures occur and corrective maintenance is maintenance carried out after failures occur.

Condition Monitoring can consist of e.g. vibration analysis and oil analysis. In these two different analyses there are several methods that can be used. The components that are of interest of condition monitoring are the gearbox, generator and the main shaft. The component of most interest, and that it has been shown is a critical component due to its impact on system availability, is the gearbox.

Life Cycle Cost (LCC) analyses have been made to calculate if it is profitable to implement CMS. The total cost, *LCC* including additional costs for implementing CMS, is compared for different alternative maintenance strategies. For a single turbine onshore versus an average turbine offshore in three strategies, and for a farm offshore where maintenance is planned using CMS in three strategies. The *LCC* without costs for CMS is called the basic case.

The first three strategies studied for the separate turbine onshore gave the following results when a CMS cost is added to the basic case; to compensate for the additional cost the preventive maintenance has to be decreased by 23 %. To compensate for the additional cost the preventive and corrective maintenance together have to be decreased by 3,5 %. The same results for the farm offshore, where an average turbine was observed, were 4,5 % and 2,5 % respectively. Decreased corrective maintenance is needed to motivate CMS, at least for the turbine onshore.

The following three strategies studied for the farm offshore gave the following results: a change from corrective maintenance to preventive maintenance with 47 % would be enough to make CMS profitable. The availability would not have to be increased with more than 0,43 % to get a reduction in cost for production loss that would cover the cost for CMS.

Sammanfattning

Vindkraftsindustrin har varit med om en stor ökning de senaste åren. Ökningen har huvudsakligen att göra med en ökande marknad, bättre ekonomiska villkor för vindkraften genom politiska beslut och utvecklingen av stora vindkraftverk och offshore-parker. Ett mål är att öka tillförlitligheten. Det är särskilt viktigt för offshore-parker där service är svårt och dyrt.

Svaret för vindkraftverksindustrin för bättre underhåll och ökad tillförlitlighet kan vara CMS (Condition Monitoring Systems) system, tillståndsövervakande system. Sådana system används flitigt i andra industrier. De övervakar kontinuerligt uppförandet av vindkraftverkets delar t ex generator, växellåda och transformator, och hjälper till att bestämma bästa tid för ett specifikt underhållsarbete. Hur dessa system kan hjälpa vindkraftverksanvändaren undersöks i denna rapport.

Ett ytterligare steg kan vara att implementera CMS som en del av Reliability Centered Maintenance (RCM). RCM, funktionssäkerhetsinriktat underhåll, är en strukturerad metod som fokuserar på tillförlitlighetsaspekter när underhållsplaner bestäms. Man vill hitta balansen mellan förebyggande och avhjälpande underhåll. Förebyggande underhåll sker före fel inträffar och avhjälpande underhåll sker efter det att fel inträffat.

Tillståndsövervakning är ett verktyg som kan användas på många sätt bland annat som vibrationsanalys och oljeanalys. I dessa två olika analyser finns flera metoder som kan användas. När det gäller vindkraft är växellådan, generator och huvudaxeln de komponenter som är av störst intresse för tillståndsövervakning. Den komponent som är av störst intresse och som det har visats är en kritisk komponent på grund av dess inverkan på systemtillgängligheten, är växellådan.

För att undersöka om CMS är vinstgivande har en Life Cycle Cost (LCC) analys utförts. Den totala kostnaden, LCC innehållande adderade kostnader för implementering av CMS, jämförs i olika underhållsstrategier. För ett separat vindkraftverk på land jämfört med ett medelverk till havs i tre strategier, och för en vindkraftspark till havs där underhållet planeras med CMS i tre strategier. LCC utan kostnader för CMS kallas grundfallet.

De tre första strategierna gav för det separata vindkraftverket på land följande resultat när en kostnad för CMS adderas till grundfallet; för att kompensera för den adderade kostnaden måste det förebyggande underhållet minska med 23 %. För att kompensera för den adderade kostnaden måste förebyggande- och avhjälpande underhåll tillsammans minska med 3,5 %. Samma resultat för parken till havs, där ett medelverk observerats, var 4,5 % respektive 2,5 %. Vi måste alltså komma åt det avhjälpande underhållet för att göra CMS vinstgivande, speciellt för det enskilda vindkraftverket på land.

De följande tre strategierna då en hel park till havs observerades var slutsatserna följande; en ändring från avhjälpande till förebyggande underhåll med 47 % skulle räcka för att göra CMS vinstgivande. Tillgängligheten skulle inte behöva öka med mer än 0,43 % för att få en reduktion i kostnaden för produktionsbortfall som skulle täcka kostnaden för CMS.

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1 Introduction

1.1 Background

The wind power industry has experienced a large growth in the past years. The growth mainly focus on a growing market and the development of large wind turbines and offshore farms. The technical availability of wind turbines is high, this has mainly to do with a fast and frequent service and not with good reliability or maintenance management. Earlier, many wind power manufacturers tried to put the high service costs on insurance companies but they are not willing to play this game anymore. Hence, the wind power manufacturer must pay the service costs on its own as long as the turbines are within the warranty or service contract. Reliability for existing turbines must increase. The topic is even more important for offshore farms where service is difficult and expensive. Private owners of wind turbines without service deals have a similar interest in reducing maintenance costs and downtime.

Could the answer for the wind power industry be condition monitoring systems (CMS)? Such systems, commonly used in other industries, continuously monitor the performance of the wind turbine parts e.g. generator, gearbox and transformer, and help determine the best time for a specific maintenance work. At the moment several companies are developing and testing such systems. The systems aim at private owners that use wind turbines from many different manufacturers, hence the CMS systems must work for wind turbines from many different manufacturers. At the moment it seems that no systems show satisfying results and they seem to be too expensive to buy compared to what they do for the separate turbine [1], [8]. It must be investigated how these CMS systems can support the wind power user.

The further step could be to implement Reliability Centred Maintenance (RCM) as a part of CMS. A RCM method is a structured approach that focuses on reliability aspects when determining maintenance plans. The method defines efficient maintenance plans by e.g. prioritising critical components and through the choice of maintenance tasks [9].

1.2 Objective

The main objective of this work is to formulate recommendations from a user perspective on the use and benefit of CMS systems for wind power applications.

1.3 Approach

To understand the wind turbine's needs when it comes to the maintenance process a general knowledge about the wind turbine was needed. By looking into how the business views wind turbines, its components and CMS and how they view certification and standardization a knowledge for what they want was found.

Through investigating how CMS could be applied to Reliability Centred Maintenance (RCM) and how this has been performed earlier in e.g. hydropower, a general knowledge was reached. Definitions of failure, availability and maintenance were necessary to come to an understanding about RCM and further on about RCM as a possible tool for wind power.

To get an understanding about CMS and what it can do, condition monitoring with vibration analysis and oil analysis has been studied in detail. The component that seems to fail the most is the gearbox [10]; it has therefore been studied in a basic way and with condition monitoring as a focus.

Some companies that operate wind turbines and wind farms were studied with attention to how periodic maintenance is carried out, type of service contracts and CMS.

To get an understanding about if an implementation of CMS in a wind turbine could be profitable a LCC analysis has been made. Present values for the total cost were here calculated in different cases, including the cost for CMS.

1.4 Main function

A wind turbine is a machine that transforms kinetic power in the wind into electricity. The main parts are rotor and hub, several bearings, gearbox, generator, brakes, control system and a part that balance the electricity. Design of the wind turbine when it comes to rotor and hub can vary, but the most common is that the axis is horizontal. That is the axis of rotation rotate parallel with the ground with two or three blades. The gearbox task is to speed up the rotation from a low speed to a speed that can operate the generator. Some turbines use special generators that work at a low speed and then do not need a gearbox. Here the focus has been to analyse a general wind turbine with gearbox.

Nearly all wind turbines use induction or synchronous generators that demand a constant or close to constant speed. Because the generator should not be too warm a cooling system is needed. The generator can be cooled in two ways either with air or with water. There are two brakes in a wind turbine; one brakes the rotor and the other is placed between the gearbox and generator and is used as an emergency brake or when the wind turbine is being repaired to avoid that the rotor starts spinning. The task of the control system is to put an upper limit on the torque and to maximize the energy production. There is also a small motor that runs a gearwheel so that the nacelle can be turned so that it always is in the wind direction. The nacelle also contains a controller that controls the different parts of the wind turbine [11], [12].

The highest efficiency is reached at the designed wind speed. At this wind speed the power output reaches the rated capacity. Therefore the power output of the rotor must be limited to keep the power output close to the rated capacity and thereby reduce the driving forces of the individual rotor blade as well as the load of the whole wind turbine structure. This can be done in three ways: stall regulation, pitch regulation or active stall regulation [13].

Due to the airfoil profile, the air stream conditions at the rotor blade change in a way that the air stream creates turbulence in high wind speed conditions on the side of the rotor blade that is not facing the wind. This effect is called the stall effect [13]. The effect results in a reduction of the aerodynamical forces and of the output of the rotor. In stall regulation the turbine is designed so that turbulence is created and thereby force and speed is controlled. These systems are most common among old turbines.

By pitching the rotor blades around their longitudinal axes, the relative wind conditions and the aerodynamic forces are affected in a way so that the power output of the rotor remains constant after rated power is reached [13]. The blades are pitched so that the speed is controlled. Active stall is a combination between pitch and stall.

1.5 Standardization and certificate

As an increasing number of wind turbines are being incorporated into electrical networks, and in some countries becoming a key part of the distribution network, the need for standardization and certificate of wind turbines is increasing.

VGB is a group of energy company members mainly from Germany who concentrate on operation experience exchange. Allianz is a company that insures wind turbines and spends large resources on identifying damage causes. The background to the problems seemed to be insufficient prototype testing, too fast new developing, insufficient dimensioning and a wrong choice of components. When it comes to operation and maintenance the background to the problems seemed to be bad documentation, insufficient maintenance effort, insufficient quality assurance and insufficient spare parts. Condition monitoring maintenance was considered a necessary condition for a reasonable operation- and maintenance cost for wind turbines in the long run. 2004 a third of the damage of electrical equipment was due to lightning. Other large groups of damage were on control equipment.

FGW (the German wind power group) works with producing guiding principles for maintenance of wind turbines. The background of this is that they earlier did not put demands on wind power distributors as they do on regular power distributors, for example on purchasing of maintenance. A more professional approach is necessary.

Corrective maintenance costs generally increase when constructions get older. The distributor has interest in the construction working with no problems for three years and that then a lot of replacement parts should be sold. If maintenance is carried out by a contractor replacement parts are included in the contract during the warranty time. After the warranty time it can be difficult for the owner to control the maintenance cost if the owner hasn't been involved in the maintenance from the start. Technical documentation for the whole construction must involve information of every component so that it is possible to replace these in a later stage [14].

Standard for components

There is a need for a common standard for description of components in a wind turbine.

Today there is a description system KKS that is used nationally and internationally for power plants. This system is used on new wind turbines in Denmark. In 2007 there will be an international standard ISO /TS 16952-1 that is built on e.g. KKS and can be used on wind turbines.

When the largest suppliers were investigated it came up that neither of Vestas, Bonus or Enercon has a description system today but they indicate the systems components in plain language. Nordic wind power has a description system for the system but not for the components. All these suppliers use plain language in their failure reporting systems. No one

of these suppliers has a computer maintenance program where the customers have access to data. There are two maintenance systems on the market, Jobtech and Datastream 7i, that are used among other things in energy production. Both of these systems are designed such that the components are built up so that the first part indicates a head group and the following part a component that is split up into smaller pieces and so on. Both those systems are Web based [15].

Standardization of CMS

As the CMS systems are gaining in significance in wind power the demands on certification increases. With its “Guideline for the Certification of Condition Monitoring Systems for Wind Turbines” that was published in 2003, GL Wind has defined a standard for security [16]. Since the introduction of this guideline several CMS have been certified and several systems are now examined [17].

At a quality-oriented examination of the internal and external state of a wind turbine the condition monitoring systems are gaining in significance. With these systems fluctuations and changes in the components of the wind turbine can be detected and corrected in good time. If the CMS is reliable this reduces more than just the costs of operating the turbine. If the turbine is equipped with CMS certified by GL Wind there are more favourable terms to receive from their insurance companies.

For condition monitoring sensors are placed on the main bearing, gearbox and generator and measure the vibrations occurring on the inside and on the surface of these components. A special software package analyses vibrations and alarms if they vary from the norm. Experts then can recommend the right measure as soon as possible. The CMS registers a lot of parameters such as wind direction, temperature of the air outside and different oil pressures.

CMS certification is a complex process, after a through examination of document and computer programs the CMS is inspected by experts from GL Wind. This involves among other things checking that [16]:

- at least the main bearing, main gearbox, generator and the tower are monitored by the CMS;
- the relevant parameters such as speed, output and temperature are recorded;
- the measurement values relating to a special state are separated from those due to normal operation
- data that are of significance for interpretation can not be lost;
- transgressions of the limit values are automatically and immediately triggering an alarm;
- the use of the CMS is also possible under extreme site conditions e.g. offshore.

The CMS certificate issued by GL Wind has a validity period of two years, after which recertification is necessary [16].

1.6 Thesis overview

In this chapter an introduction to the problems to be solved has been presented together with some basics on wind power and standardization that is gaining in significance.

In the following chapters the aim is to at first describe some theory involving some general definitions to get to an understanding about maintenance, RCM and condition monitoring.

Later on different companies that operate wind turbines and farms are presented and analysed according to periodic maintenance, service contracts and CMS.

Finally a Life Cycle Cost (LCC) analysis is carried out and the total cost for a wind turbine and a wind farm is calculated first without a CMS and then in different strategies with the affects of a CMS.

2 Theory

This chapter on theory opens with some common definitions like failure, reliability and availability. Further on, maintenance is described in its different forms and reliability centered maintenance, (RCM) is explained and some descriptions of RCM are shown. Condition monitoring is explained in a basic way and for the gearbox and an introduction to Life Cycle Cost (LCC) is presented. RCM as a tool for wind power is finally discussed.

2.1 Definitions

To get to an understanding about maintenance and RCM and further on about RCM as a possible tool in wind power some definitions are necessary to understand. These are:

Item

Any part, component, device, subsystem, functional unit, equipment or system that can be individually considered [18].

Asset

A formally accountable item [18].

Failure

Termination of the ability of an item to perform a required function [18].

The bathtub curve is the most common way to describe a components failure intensity, see Figure 2.1. The failure intensity indicates how many times during a certain time that a component fails. The name bathtub curve comes from the assumption that the component has a starting period with running-in failures, then a period with constant failure intensity and in the end an increasing failure intensity where the component comes closer to its expected life length.

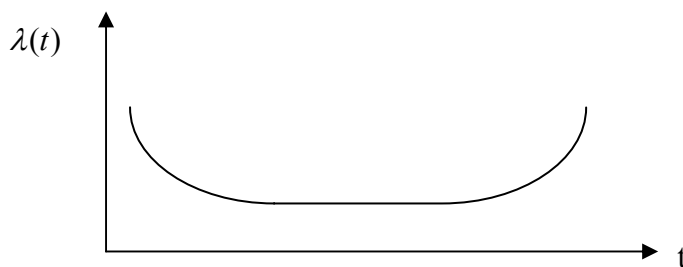


Figure 2.1 The bathtub curve

Mathematically this curve is desirable, because it gives a period of constant failure intensity which makes it reasonable to assume that failures occur according to a Poisson-process, that is failures occur by chance in time [19].

Availability

The concept of availability has several different definitions. According to Holen et al [20] the definition is:

The probability that the component, system is capable of functioning at a time t .

Some types of availability are [21]: availability, asymptotic availability, asymptotic average availability, average availability and instantaneous availability.

According to Swedish standard [21] the definition for asymptotic availability is:

$$A(\infty) = \lim_{t \rightarrow \infty} A(t) \quad (2.1)$$

where A describes availability

or

$$A(\infty) = \frac{m_s}{m_s + MDT} \quad (2.2)$$

where m_s denotes the average service time and MDT the Mean Down Time.

This concept can be used if failure intensity and repair intensity are constant. When these conditions are valid the definitions for availability and asymptotic availability are the same and is called availability [19].

According to Holen et al [20] the asymptotic availability is identical to asymptotic average availability when the threshold value for the asymptotic availability exists and this is then called availability A . The availability A is defined:

$$A = \frac{E(T)}{E(T) + E(D)} = \frac{MTTF}{MTTF + MTTR} \quad (2.3)$$

where T is life length times and D is repair times

Mean Time Between Failure, MTBF

Mean Time Between Failure is the most common way to determine a maintenance interval. It indicates the time from a components failure to its next failure. This time include MDT (Mean Down Time) and MTTF (Mean Time To Failure).

$$MTBF = MDT + MTTF \quad (2.4)$$

According to Holen et al [20] MTTF can be written:

$$MTTF = E(T) = \int_0^{\infty} tf(t)dt \quad (2.5)$$

MTBF can with help of historical data be estimated to get an approximated value. “The large numbers law” is valid at estimation of values and says that when the number of observations (N) goes to infinity the value of the estimated parameter goes to the parameter’s true value [22].

$$MTBF = \frac{\sum_{n=1}^N t_n}{N} \quad (2.6)$$

t_n = time between failure for failure n , N large

If the component is not in operation 100% of the time this must be taken into consideration.

Mean Time To Recovery, MTTR

MTTR together with MTW is the Mean Down Time (MDT):

$$MDT = MTTR + MTW \quad (2.7)$$

MTTR is estimated with the help of historical data in the same way as MTBF:

$$MTTR = \frac{\sum_{n=1}^N t_n}{N} \quad (2.8)$$

t_n = repair time for failure n , N large

MTW is the mean waiting time and is also estimated with help of historical data.

Failure rate

Failure rate, λ , indicates how many times per unit time that a component fails. MTBF indicates how long a time passes between each failure. The relation between these is therefore:

$$\lambda = \frac{1}{MTBF} \quad (2.9)$$

Reliability

Ability of an item to perform a required function under given conditions for a given time interval [18].

2.2 Maintenance

According to a Swedish standard maintenance is a combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function [18].

2.2.1 Preventive maintenance

Maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item [18]. Preventive maintenance means that the maintenance is planned and periodical. The maintenance is carried out with equal intervals to prevent that failures occur [19].

Scheduled maintenance

Preventive maintenance carried out in accordance with an established time schedule or established number of units of use [18].

Condition based maintenance

Preventive maintenance based on performance and/or parameter monitoring and the subsequent actions [18].

Data about the components history is used together with statistical methods to predict when there is a need for maintenance. To predict when maintenance is needed history about when, how and why the component have failed [19]. A condition control is performed to in time detect that a failure is occurring [23].

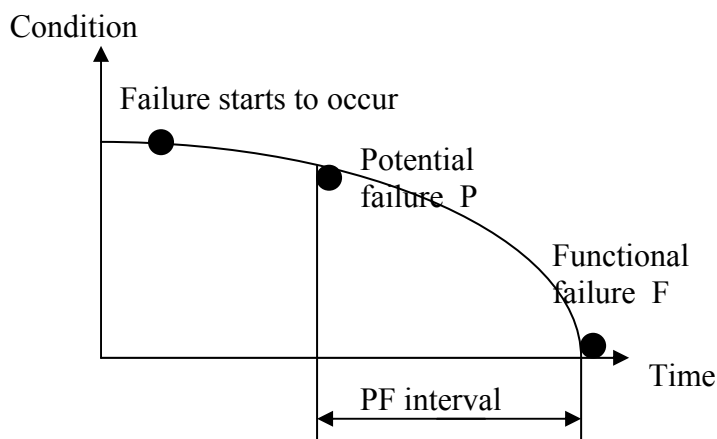


Figure 2.2 PF-interval

A PF-interval shows how an interval between a potential failure and a failure is determined (see Figure 2.2) The potential failure is at the time when the failure can be measured. PF-interval is the time from that a change can be measured to that a failure occurs. With a known PF-interval test intervals can be determined to be able to attend to the deviation before a

failure occurs. The test-interval cannot be longer than the PF-interval [19]. The current time interval for the measure is as a recommendation determined to half the PF-interval [23].

2.2.2 Corrective maintenance

Maintenance carried out after failure recognition and intended to put an item into a state in which it can perform its required function [18].

No maintenance is carried out as long as a component is working. When the component is failing it is repaired or removed. A component that is repaired can be repaired to “as new” or as before it failed [19].

2.3 Maintenance optimization

The general goal for maintenance optimization is to minimize total costs or maximize resources of maintenance. If the maintenance should be operated in a good way there are some goals that should be fulfilled. Examples on these are [24]:

- The maintenance should be operated so that the equipment has high availability and so that safety is withheld – this should be done at a total cost that is as low as possible.
- The equipment should be maintained to have a long lifetime and retain its quality level.

The question that often is discussed in maintenance consistence is the balance between preventive and corrective maintenance and the relationship between those. In practice it is difficult to find the optimal relationship between them. It is very difficult to determine which corrective maintenance cost is associated with a particular amount of preventive maintenance see Figure 2.3.

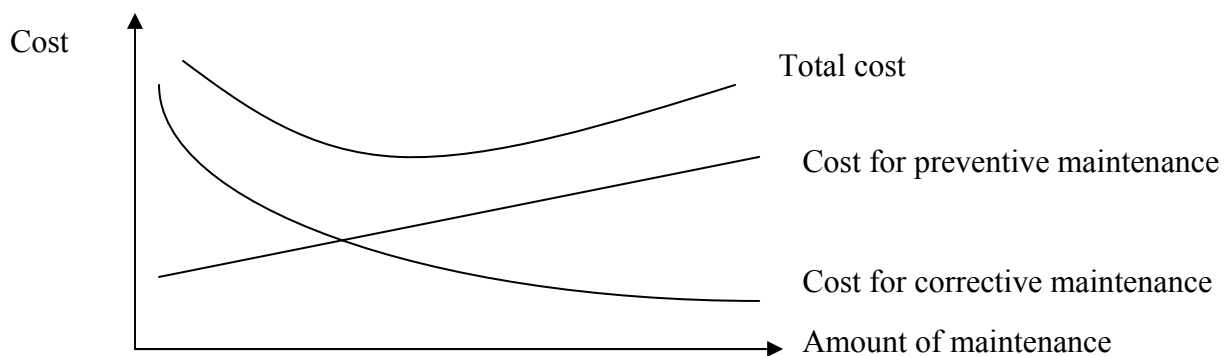


Figure 2.3 Balance between preventive- and corrective maintenance [24]

2.4 Reliability centered maintenance, RCM

Reliability Centred Maintenance, RCM, gives a systematic method to balance between preventive maintenance and corrective maintenance, and to choose right preventive maintenance activities for the right component at the right time to reach the most cost efficient solution [25]. A RCM method is a structured approach that focuses on reliability aspects when determining maintenance plans. The method defines efficient maintenance plans by e.g. prioritising critical components and through the choice of maintenance tasks [9].

RCM has its origin in the civil aircraft industry and the Boeing 747. The first description came in 1978 by Nowlan. The introduction in nuclear power came in 1980 and in hydro power in 1990.

RCM is characterised by:

1. Maintaining system function
2. Identifying failure modes
3. Prioritising functions
4. Choosing efficient maintenance measure

There are several descriptions of the process to define a RCM plan, some are:

1. Smith 1993 – seven steps
2. Nowlan – steps for a first RCM plan
3. Moubray – seven questions

RCM according to Smith

Smiths method is based on theoretical analysis models and decision tree analysis [25], the seven steps are:

1. Choice of system and information collection
2. Boundary making of the system
3. Systems description and function block diagram
4. System function and function losses
5. Failure Effect and Function Analysis (FMEA)
6. Decision tree analysis
7. Establishment of maintenance measures

FMEA

FMEA, Failure Mode and Effect Analysis, is used in reliability analysis and with this method the connection between possible failure modes for a construction and the failure effects that these give rise to can be determined [31]. The method was introduced by the aircraft manufacturer Boeing in 1957. The method was developed during the fast technical development in 1940-1960.

The purpose of the method is to find all the ways that the product can fail. Three questions are answered, these are:

1. What failures/events could appear?

2. What are the effects of the failures/events?
3. What are the causes of the failures/events?

Then the failures probability, seriousness and possibility of discovery should be estimated. To perform this the system is being divided into several sub systems. When the three questions have been answered the frequency with which the failure can occur is indicated with a number between e.g. 1 and 10. Then a number indicates the seriousness of the consequence. Finally a number indicates the probability for discovery. These numbers are multiplied into a combined index number, for which a higher value indicates a worse failure. This number is called risk priority number. This gives a ranking list for the failures, from which using the size of the risk priority number one can make an estimation of the seriousness of the failures and then make a measurement.

RCM according to Nowlan

Nowlan defines a first RCM plan where information is limited as follows [25]:

- partitioning the equipment into object categories in order to identify those items that require intensive study
- identify those items that require intensive study
- identify significant items that are those that have essential safety or economic consequences and hidden functions that require scheduled maintenance
- evaluating the maintenance requirements for each significant item and hidden function in terms of the failure consequences and selecting only those tasks that will satisfy these requirements
- identifying items for which no applicable or effective task can be found, then either recommending design changes if safety is involved, or assigning no scheduled maintenance tasks to these items until further information becomes available
- selecting conservative initial intervals for each of the included tasks and grouping the tasks in maintenance packages for application
- establishing an age-exploration program to provide the factual information necessary to revise initial decisions.

Mourbray's RCM II

To analyze the maintenance aspects of a system and its components, the first step is to identify the system items, and which of these that ought to be analyzed [25].

According to Mourbray you should answer seven questions when you identified the systems items and which of those that should be analysed:

1. What are the functions and performances required?
2. In what ways can each function fail?
3. What causes each functional failure?
4. What are the effects of each failure?
5. What are the consequences of each failure?
6. How can each failure be prevented?
7. How does one proceed if no preventive activity is possible?

In the first point it is stressed that when the function is specified it is important to indicate a certain level that the unit should meet. Functions are what an asset is expected to perform but can also be anything an asset has to comply with, such as colour or shape. Functions are divided into primary and secondary functions. The primary functions describe the main purpose of the asset. Secondary functions describe additional features the asset should meet such as colour or safety aspects [27].

Then there is indicated in which ways the unit not can cope with the demands. The cause of the failure is then described and here one should be careful so that this is analyzed on the right level.

Too much detail can make the process long and expensive, while too low a detail level could make the process meaningless.

In point four the course of events at a failure should be described. Among other things physical or environmental damage and how to restore the equipment should be in the description.

The consequences of a failure are divided into three categories:

1. Safety- and environmental consequences
2. Operational consequences
3. Non-operational consequences

If a person could be injured or if the failure could cause an environmental law to be broken the consequence is classed as a safety- and environmental consequence. Operational consequences affect costs regarding production and operation. The non operational consequences only gives cost in the form of operations.

Then a decision tree is used to determine which maintenance should be carried out. Depending on the consequence classifying of the failure and what kind of maintenance is applied the best maintenance strategy is determined [25].

Benefits with using RCM

When engineers from both system/operation, maintenance and construction work together a much better whole solution is reached. The following benefits can be identified [24]:

- Through a careful analysis of the failures the amount of preventive maintenance often can be reduced or replaced with corrective maintenance.
- Instead of doing large reviews at determined times one has instead started to do more directed efforts this tanks to condition monitoring. Everything does not have to be attended to.
- Spare parts carriage has decreased.
- Bad construction methods are discovered at an early stage.

Developments of RCM; Reliability centered asset management, RCAM

The aim of RCAM is to relate preventive maintenance to the total maintenance cost and system reliability [28]. The method is developed from RCM principles attempting to relate

more closely the impact of maintenance to the cost and reliability of the system [29]. The aim is to see with quantitative methods the effect on a component level of preventive maintenance on system reliability results.

As a first step in the method, the critical components for the system reliability are identified from a sensitivity analysis. The critical components are studied further, focusing on the impact of maintenance measures. The relationship between reliability and maintenance has been established by relating the effect of preventive maintenance to the causes of failures for the component being assessed.

One of two of the following approaches for the reliability of the components due to maintenance is used [29]:

1. Component reliability is assumed to be affected only by preventive maintenance. A constant ratio between failure rate and the effect of preventive maintenance is proposed.
2. The second model expands the first model to also be able to be dependent on time.

The information deduced in the critical component analysis is used when comparing different preventive maintenance strategies with respect to reliability and cost.

The main stages of the RCAM approach are as follows [29]:

1. System reliability analysis: defines the system and evaluates critical components affecting system reliability.
2. Component reliability modelling: analyzes the components in detail and, with the support of appropriate input data, defines the quantitative relationship between reliability and preventive maintenance measures.
3. System reliability and cost/benefit analysis: puts the results of stage 2 into a system perspective, and evaluates the effect of component maintenance on system reliability and the impact on cost of different preventive maintenance strategies.

These three stages emphasize a central feature of the method: that the analysis moves from the system level to the component level and then back to the system level.

RCM in hydro power

Vattenfall Vattenkraft has developed a RCM model for its hydro power stations that are being implemented, the model is similar to Moubray's RCM II in many aspects [25]. It approximately follows the same steps but differs when maintenance strategy is chosen [9].

RCM according to Vattenfall Vattenkraft (VVK RCM) [25]:

1. Define functions
2. Establish function failure
3. Establish failure modes
4. Perform risk analysis
5. Establish possible maintenance tasks
6. Analyses and decide on maintenance strategies

Each function in the standard analysis is studied and if necessary functions are added and removed.

For each function all relevant functional failures are considered. The standard analysis is used and functional failures are added or removed if needed.

All reasonable causes for each functional failure are now listed. These are called failure modes. The standard analysis is used as a reference [9].

Risk analysis is performed for every failure mode. The whole course of events that led to a failure is identified. To then estimate the risk for a failure how often a failure occurs is being approximated and how serious the consequences are by the failure. A failure matrix is being used.

There are eight different consequence categories for each failure:

1. Break down costs
2. Costs
3. Work environment
4. Flow to dams
5. Environmental damage
6. Personal esurience
7. Productions stop
8. Efficiency

For each of these categories that are applicable for the failure mode in question the seriousness of the consequence is measured on a scale of one to three. Then how often the failure occurs is approximated. When this is used in the risk matrix it gives a number between 0 and 5 that describes the risk of the failure. If you get a risk number that is three or higher preventive maintenance should be used, otherwise corrective maintenance should be used [25].

Then the different maintenance possibilities are studied. A decision tree is used for help. First, corrective maintenance tasks are documented. Then condition based maintenance which is divided into continuous and scheduled maintenance is specified if it is possible to conduct. If the probability of the failure increases with time and there is a possibility to use predetermined tasks these are recorded. For a hidden failure it is investigated whether there are any feasible failure finding tasks. Finally possible redesign or education of personnel to avoid the failure is documented [9].

To economically decide what kind of maintenance to use some additional input data is needed. This input data includes stop time and costs due to loss of production, the cost of personnel to perform maintenance, cost of new parts for damaged equipment and other costs in connection with the maintenance tasks and breakdowns. There is also the possibility of specifying if the maintenance can be planned ahead of time and how much this could replace costs for the loss of production [9].

The VVK RCM has an extensive approach where all feasible maintenance tasks are compared. This requires a lot of work but yields a resulting maintenance strategy that is optimal regarding the tasks studied [9].

Similarities between VVK RCM and RCM II

VVK RCM and RCM II have a great deal in common. The main difference between the methods is that RCM II has a decision diagram where certain maintenance strategies are preferred and if feasible picked. VVK RCM has a more complex way of deciding maintenance strategy. All tasks are considered and with the help of a risk and cost analysis the best maintenance strategy is picked [9]

2.5 Condition Monitoring

As a part of condition based maintenance, condition monitoring could be used to get a constant monitoring of each condition.

Condition monitoring is the use of advanced technology for the purpose to monitoring a components condition and predicting failures in each condition. Techniques that are included in condition monitoring are, for example, vibrations analysis and this is what is of importance in this study. We have determined to observe the gearbox and its bearings in detail, and thereby also observe some oil analysis methods. CMS are used today in many other energy systems such as hydro and nuclear power. Introduction of CMS means that maintenance can be carried out in a much more efficient way. Today in wind power there is mostly periodic maintenance and this is often twice a year [1]. Instead one could attempt to get an optimal maintenance strategy with predictive and corrective maintenance. In this work CMS could be a great help. The German company Nordex already has combined “reliability oriented maintenance” with their CMS [30]. That is a combination of reliability centred maintenance with CMS.

A definition of condition monitoring is “A means to prevent catastrophic failure of critical rotating machinery”. An other is “A maintenance scheduling tool that uses vibration, infrared or lubrication oil analysis data to determine the need of corrective maintenance actions” [33]. The theme of these definitions are that condition monitoring is only a maintenance tool. But it is so much more. It can provide the means to improve the production capacity, product quality and overall effectiveness of the manufacturing and production of turbines. Condition Monitoring is a management technique that uses the regular evaluation of the actual operation condition of turbine equipment, production systems and turbine management functions to optimize total turbine operation. Condition monitoring can also be a production management tool. The data derived from the programme can provide the information needed to increase production capacity, product quality and overall effectiveness of the production function. To be an effective maintenance management tool the condition monitoring programme must be combined with a viable maintenance planning function that will use the data generated to plan the appropriate repairs [31].

For the future the following is expected [32]:

- The development of sensors, and other low-cost on-line monitoring systems that could permit the cost-effective continuous monitoring of key equipment items.

- The increasing provision of built-in vibration sensors as standard features in large motors, pumps, turbines and other large equipment items.

Increasingly sophisticated condition monitoring software, with rapidly developing "expert" diagnosis capabilities.

The acceptance of Condition Monitoring within the "mainstream" of Operations and Maintenance.

Increasing integration, and acceptance of common standards for interfacing Condition Monitoring software with Process Control software.

An increasing focus on technologies to improve equipment reliability and performance, rather than to merely predict component failure.

Monitoring

Wind power is getting more established as an alternative to fossil fuels. As the size of wind turbines and farms increase there must be new ways to minimize downtime and maximize availability and profit. To do this there have been introduced ways to perform condition monitoring [33].

Wind turbines are complex machinery that transform the kinetic energy in the wind into electricity. To receive a large amount of electricity the turbine must have a large diameter. Hence the turbines speed is low and it must be speeded up to a speed that fits the generator. The turbine operates a generator through a speeding gearbox usually with a planet gear and one or two parallel gears. There are also several bearings that carry large radial stress and therefore must be carefully monitored [33].

There are two groups of vibration frequencies in a wind turbine, gear frequencies and bearing frequencies. In a typical machinery there are typically three gear frequencies seen from measurements of several gears. There are several axes that are supported by bearings that produce four different frequencies. It's easy to see that the combination of frequencies makes frequency analysis a formidable task [33].

Due to the fast growth of wind turbines the technique has become old. There are reports on injuries on gearboxes, bearings and rotor blades. Insurance companies complain over large damages and introduce maintenance restrictions. Is the wind power industry really going through a crisis? A possible solution to avoid damage is monitoring [34].

The most common monitoring procedure for wind power today is the so called Wind Farm Monitoring that focuses on monitoring produced energy but that also registers failure messages from the control system of the wind turbine. From the control system can be seen e.g. temperatures of oils and acceleration in vibrations. Mostly a failure already has occurred when the control system gives an alarm [34].

In Wind Farm Monitoring there are often periodical inspections used when the whole machinery is checked over. Damage can then be discovered as cracks in rotor blades and foundations and failures on other components such as the gearbox and other mechanical parts. But these inspections do not give answers on when and how damage has occurred [34].

New ways of monitoring

To avoid preventive replacement of components Condition Monitoring is now widespread. In practice there are two ways of condition monitoring. One way is to monitor continuously with suitable sensors united with the control system that alarms as soon as data is changed. For example the frequencies of the gearbox can be measured and compared to original frequencies. This results in failures being able to be found at an early stage. Another way is periodical mechanical diagnosis where inspections of components are carried out periodically of gearbox and generator with measuring equipment and compared with the latest measurement. With this method the failure process can be found but failures cannot be found as fast as when monitoring constantly [34].

Maintenance costs for offshore wind turbines seems to high to make such projects economically viable. A large part seems to be corrective maintenance, onshore preventive- and corrective maintenance parts are the same. To reduce costs for corrective maintenance offshore condition monitoring should be introduced to discover failures early. Then repairs could be better planned and this gives shorter down times and smaller costs. Use of condition monitoring has grown the last years in several businesses and now the interest is increasing in the wind power industry [35].

Vibration analysis is the most known technology for performing condition monitoring, especially for rotating equipment. For wind turbines wheels and bearings in the gearbox, bearings in the generator and main bearing can be monitored satisfactorily. For other applications than wind power stress and speed are constant during long periods, which makes signal analysis easier. For wind turbines these experiences are limited [35].

The control systems in wind turbines have increasing functionality. Some of their functions come close to the concept of condition monitoring. With relatively low costs they could be developed to find failures quickly. There is an increasing interest in blade monitoring but it is still a very costly method. There is however a strong development in this area at the moment with many parties involved. Condition monitoring demands knowledge and experience. Signal interpretation and monitoring are often outsourced to companies that are also involved in maintenance. These companies need access to the systems in question. Standardization in communication and interface is of increasing importance for the adjustment of these systems [35].

The adjustment system is one of the most vulnerable system in a wind turbine. For large wind turbines the adjustment system is a part of the security system. It is of increasing importance for electricity control and stress reduction to be able to adjust the turbine. It is now obvious that it is important to measure vibration in the gearbox. Specialized companies provide the wind turbines with system for vibration analysis. The situation for the main bearing is identical with the gearbox. Together with the gearbox most systems even monitor the main bearing and the bearings of the generator. When it comes to sound registration personnel listen to the turbine and hear certain signs of failure. This is based on long experience and can be difficult to extract from noise signals. There are already some practical examples of blade monitoring, the company LM for instance has a system that detect unreasonable vibration levels and sends a message to the company [35].

Integrating with maintenance tools

Numerous programs have been developed to present condition monitoring results in a form suitable for inclusion in a maintenance management system. Information may then be constantly updated providing data which is required for a repair action, and bench marks to help in measuring the effectiveness of maintenance operation. Trends can be established and evaluated; data for projections are an unlimited source of management information. At a primary level “unit condition reports” may be itemised to indicate problems and to recommend corrective action to maintenance personnel. The current condition of equipment may be indicated in terms such as satisfactory, marginal or critical. Any discrepancies or deficiencies in either mechanical or lubricant condition can then be identified and appropriate corrective action specified [31].

Diagnosis, subsequent to analysis, requires considerable experience and knowledge of the interaction of the lubricant, mechanical equipment and the working environment. Aside from helping to establish normal wear patterns, concentration profiles are also useful in comparative evaluations of equipment or operating conditions, lubricants, components and maintenance procedures. Close supervisory control is essential to a viable monitoring programme. The computer system can assist in this responsibility by keeping track of sampling schedules and reporting on equipment due or overdue for monitoring [31].

The visual inspection of machinery using the unaided eye or some form of optical assistance is the simplest and most cost effective method of condition monitoring. Its application may though be limited to stationary equipment. Vibration signal analysis is well supported by equipment that is readily available and relatively cheap. Its implementation benefits from the use of non-intrusive transducers which can be packaged as small hand held portable devices. This means that many measurements can be taken usefully at several access points, resulting in wide failure coverage for very little equipment cost. The fluid and wear debris analysis approach to condition monitoring is restricted to circulatory arrangements such as lubrication systems. Where it can be applied, bearings and gears can be monitored [31].

2.5.1 Vibration analysis

The condition of a bearing can be defined indicated by noise. The higher rpm and the higher stress the bearing is exposed to, the sooner it gets worn out [36]. Since a few years ago there are computer based equipment which can measure the sound and evaluate the condition of the bearing. Such equipment could give valuable information about the bearings of the wind turbine. A benefit with this should be that no one need to go out to the wind turbines and climb the tower to listen to the bearings.

The turbine Elida

In the beginning of 2000 there were no products in the market for monitoring of bearings, that were suitable for wind turbines [36]. But many wind power manufacturers said that they were going to provide their offshore wind turbines with monitoring equipment.

In the turbine Elida on Risholmen in the archipelago of Gothenburg, nine vibration sensors were assembled to monitor bearings on the main axis, gearbox and generator. The system that was installed on Elida was SKF's CMS system WindCon [5], [17].

Information from the vibration givers is collected by a unit in the nacelle and the information is sent to a unit on the ground of the tower where a computer work of the information is made. The owner than can get information about the bearing's vibration limits and frequency contents through the Internet. The system contents two different alarms; one that gives a first indication on a higher vibration level and one that indicates that the bearing must be changed [36].

A bearing expert can from these signals read what part of the bearing has been damaged, by comparing vibration signals with the bearing maker's information of the bearing. How long the turbine can be run without problems is determined by the nature of the damage. The monitoring system could minimize the maintenance costs for the wind turbine [36].

History

Vibration analysis is the dominant technique used for condition monitoring [31]. Using vibration analysis to detect machine problems is not new. In the 60s and 70s US Navy, petrochemical and nuclear power industries invested heavily in the development of analysis techniques based on noise or vibration. By the early 80s the instrumentations and analytical skills required for noise-based condition monitoring were fully developed.

Basics

Condition monitoring utilizing vibration signature analysis is based on two basic facts:

- All common failure modes have distinct vibration frequency components that can be isolated and identified.
- The amplitude of each distinct vibration component will remain constant unless there is a change in the operation dynamics of the machine.

It is normal for machines to vibrate and make noise. Even machines in a perfect condition will have some vibration and noise associated with their operation. It's therefore important to remember that:

- Every machine will have a level of vibration and noise, which is regarded as normal.
- When machinery noise and vibration increase, some mechanical defect or operating problem is usually the reason.
- Each mechanical defect generates vibration and noise in its own unique way.

If a problem can be detected and analysed early, before extensive damage occurs then:

- Shutdown of the systems for repairs can be scheduled for a convenient time
- A work schedule together with requirements for manpower, tools and replacements parts can be prepared before the system is shut down.
- Extensive damage to the machine resulting from forced failure is minimized.

As a consequence of this repair time can be kept short, resulting in less machinery downtime. The detection would first require periodic manual vibration measurements on each critical machine. High performance machines, which develop problems very fast, are not well suited for periodic monitoring. For these systems, on-line, continuous, automatic monitoring is required using vibration sensors located at critical points on the machine. When the vibration exceeds pre-set levels, a warning sounds or the machine shut down automatically [31].

Techniques

Time domain vibration signals can yield enormous amounts of information. Several techniques have been used in machine condition monitoring. Some techniques are waveform, indices, synchronous average, orbits and statistical methods [31].

Waveform analysis consists of recording the time history of the event on a storage oscilloscope or a real time analyser. Apart from an obvious fundamental appreciation of the signal, such as if the signal was sinusoidal or random, it is particularly useful in the study of non-steady conditions and short transient impulses. Discrete damage occurring in gears and bearings, such as broken teeth and cracks, can be identified relatively easy. Waveform analysis can also be useful in identifying beats and vibrations that are non-synchronous with shaft speeds, and in machine coast down analysis waveforms can indicate the occurrence of resonances.

Indices are also used in vibration analysis. The peak level and the RMS (Root Mean Square) level are often used to quantify the time signal. The peak level is not a statistical quantity and is not reliable in detecting damage in continuously operating systems. The RMS value is more satisfactory for steady-state applications.

Synchronous averaging is the time signal averaged over a large number of cycles, and synchronous with the running speed of the machine. This technique not only removes the background noise, but also periodic events not synchronous with the machine being monitored. It is especially useful in gear-vibration diagnosis where multiple shafts are present. All components not synchronous with the shaft of interest can be deleted.

When displaying time waveforms obtained from two transducers whose outputs are phase shifted by 90 degrees, on an oscilloscope where the time base is substituted with the signal from one of the probes, patterns known as Lissagous figures are obtained. When shaft relative displacement probes are used, the pattern obtained is the shaft orbit. This can be used to indicate journal bearing wear, shaft misalignment, shaft imbalance, lubrication instabilities in hydrodynamic bearings and shaft rub.

Statistical analysis can also be carried out on time domain data. The probability density for example is the probability of finding instantaneous values within a certain amplitude interval, divided by the size of the interval. All signals will have a characteristic probability density curve shape. These curves if derived from machinery vibration signals can be used in monitoring machine condition [31].

Digital fast Fourier analysis of the line waveform has become the most popular method of deriving the frequency domain signal [31]. The signature spectrum obtained can provide valuable information with regards to machine condition. Enveloping or demodulating the time

waveform prior to performing the Fast Fourier Transform (FFT) is also gaining in popularity. Spectral information can also be derived using analogue filter sets tuned to passing the information only in bands of interest. The vibration characteristics of any machine are to some extent unique due to the various transfer characteristics of the machine [33]. The method of assembly, mounting and installation of the machine all play a part in its vibration response. When a machine has been commissioned a signature spectrum should be obtained under normal running conditions. This signature will provide a basis for later comparison in order to locate those frequencies in which significant increases in vibration level have occurred [31].

2.5.2 Oil analysis

In wind power it is difficult to see a breakdown according to oil failure. It is often already too late when it is detected and sometimes it is not detected at all. To find defects in the oil that can give an indication of failure continuous measurement is needed [1].

Oil analysis is a technique that has been traditionally used in the industrial market place to determine the condition of those lubricants commonly used in turbine and equipment. This analysis has also been used on automotive equipment for many years to determine the condition not only for the oil but also of the equipment. When correctly applied the analysis techniques involved can be used on oil samples from industrial turbines and equipment, to establish the condition of the machine as well as the state of the lubricant [31].

Tribology

Tribology is a general term referring to the design and operating dynamics of the bearing, lubrication and rotor support structure of machinery. Several tribology techniques can be used for condition monitoring. These include e.g. lubricating oil analysis which is an evaluating technique that determines the condition of lubrication oils used in mechanical and electrical equipment. Some form of lubrication oil analysis will provide an accurate breakdown of individual chemical elements, both oil additive and contaminants, contained in the oil. A comparison of the amount of trace metals in successive oil samples can indicate wear patterns of oil-wetted parts in turbine equipment and will provide an indication of the risk of machine failure. Tribology analysis has until recently been slow and expensive. Microprocessor-based systems are now available that can automate most of the lubricating oil analysis. For example there is the possibility of determining the most cost effective interval for oil change [31].

Methods

Oil analysis methods are spectrometric techniques used for the examination of oil and for indicating the elemental chemical composition of the debris present, as well as the concentrations of the individual elements detected. The major elements present in oil samples result from the wear of ferrous and non-ferrous metallic components, the ingress of extraneous matter such as dust and the lubricant with its associated additives. The results of the analysis are normally reported as parts per million of the individual elements, and the size of the wear debris particles contained within the lubricant sample often determines the type of spectrometric technique used.

Some examples of techniques of oil analysis are Atomic Absorption, Infrared, Atomic Emission, Inductively Coupled Plasma, X-ray Fluorescence and Energy Dispersive X-ray Analysis [31].

Atomic absorption is used for wear debris analysis and relies on the various elemental atoms absorbing light energy of specific wavelengths. The infrared spectroanalysis technique detects and measures molecular compounds. Atomic Emission is also used for debris analysis. It is a technique where a spectrum is formed by excited atoms or ions producing wavelengths relating to the elements present. Inductively Coupled Plasma is also used for the analysis of wear debris and oil additive elements. X-ray Fluorescence is also used for wear debris analysis and is a technique where the oil sample is bombarded with X-rays. Energy Dispersive X-ray Analysis is a technique used in conjunction with a scanning electron microscope for the analysis of dry wear debris.

2.5.3 The Gearbox

Gearboxes are relatively difficult to monitor as they contain many inner components. They are also known to be problematic when they are applied in wind turbines. Many wind turbines have a three stage gearbox with a first stage a planetary gear and then two stages parallel gears. There are also several bearings and gear wheels. It is a complicated system in which it is difficult to find the source of the failure. Sensors are used to localize avoiding revolutions and in that way localize failure. A complex several step gearbox can be measured with four to six accelerometers. Wind turbines work in a constantly changing environment. This can lead to injury that maybe not is detected until the future. A multiple parameter approach is necessary to detect failures. Alarm where critical frequency areas are checked out are efficient strategies to detect failures. When no reference or standard is available statistical alarms are efficient [37].

Basics

Gearboxes have many different designs. To notice the similarities you have to move to basic design. All gearboxes have a containing case, a lubrication system and gears held in mesh by axial and radial supporting bearings. The dissimilarities involve type and number of gears and bearings, configuration and number of gear meshes, gearbox size and wear and failure modes and rates [38].

Monitoring strategies include Run To Failure, Time Based Overhaul, Reliability Centered Maintenance, periodic monitoring, continuous monitoring and health assessment (Condition Based Maintenance) [38].

Gearbox wear and failure usually result from wear and failure of the primary load carrying elements such as shafts, gears and bearings. These parts are subject to normal metal to metal contact during wear-in and also during operation often causing prolonged wear in advance of failure. These parts are also subject to cyclic loading which results in surface and structural fatigue cracks and ultimately in failure [38].

Vibration monitoring

The most prevalent diagnostic technology for gearboxes is vibration monitoring [38]. The analysis of gearbox vibration data can be broadly divided into two categories; spectral analysis and feature analysis. Spectral analysis include a number of techniques that are all related to a frequency or order based Fast Fourier Transform (FFT) of the vibration data. The FFT is a plot of amplitude of the vibration signal as a function of frequency. From this plot individual frequencies can be associated with a particular gear mesh or bearing race or roller pass frequency. Changes in these signal amplitudes can be used to indicate degradation in these components and the onset of failure.

Oil analysis

Oil Debris Monitoring can provide a good backup failure detection technology to vibration monitoring, especially in complex gearboxes or where vibration levels are high enough to render conventional vibration analysis ineffective. Elemental data can, in some cases, indicate which gearbox component part is wearing. Quantity of debris and size range of the debris can indicate the degree of wear and the rate of degradation of the ferrous components in the gearbox [38].

Maintenance

Maintenance Analysis is often a valuable tool to formalize the process and create a rational basis for diagnostic choices [38]. The decision strategy must address two basic questions:

1. What are the consequences of an undetected gearbox failure?
2. What is the optimum diagnostic and maintenance approach to avoid these consequences?

The consequences of a gearbox failure can be characterized broadly in two categories: safety or financial. In most cases the financial consequences play a major role. Usually a maintenance period is planned at convenient intervals [38].

New demands and challenges

Gearboxes are one of several components that must work in ways that were not needed before, wind power put other demands on the components. After a long period of failures experts now agree that failure to adjust bearings is the cause of the problem. Many people are now beginning to speak to each other in detail about what causes the problems and how to solve them. Gearbox problems have been a common failure in wind turbines for a long time and are so still in new models [39]. Manufacturers of gearboxes can't handle the need for larger and cheaper components in wind turbines. Nearly all wind power companies have suffered from failures in gearboxes. Many gear parts are held in operation for too long and must be taken out of the nacelle for a total repair. The cost can amount to the cost for a whole new gearbox. Improved oil filtering and better knowing of the parts will allow failures to be discovered earlier [37]. This does on the other hand demand continuous monitoring [1].

The proprietary nature of the business is a problem when it comes to problems with gearboxes. “No one wants to say the truth to each other” says Mark Michaud on REM Surface Engineering. American Gear Manufacturers Association (AGMA) is pushing on standardisation and this has made that many experts from many different companies now work together. The standard AGMA 6006 is called a cook-book for how to design gearboxes. But all represented seems to have different opinions anyway.

The sheer size and complexity makes the wind industry a difficult industry when it comes to bearings [39]. Leading manufacturers admit that there is room for improvement. But the fast growth of wind turbines has made it difficult to keep up. The wind industry of today demand large diameters of the bearings and these bearings are the largest bearings made. The standardized use of spherical bearings seems to have been a mistake. It was shown that spherical bearings didn't work so well in large planetary gears and that they didn't reach the expected lifetime.

Some think that it will take years before we really know how well the technology of today is working. It's not in the nature of technology that machinery gets larger. Machinery often has to work for a lifetime before changes are made. This hasn't been the case with wind industry. It remains to be seen if technology gets to rest where it is now or if a step to even larger machinery is taken without years of experience data. Experts now try to come around the problem of absent data by doing simulations. This is a way for the wind turbine manufacturers and manufacturer of gearboxes to cooperate. Such tests don't on the other hand give enough information. To get enough information the wind turbine and gearbox must be monitored during its whole lifetime.

The gearbox and its bearings must withstand loads not seen in other industries. There is a debate about knowledge and knowing when it comes to involved loads. The big problem has been that the loads are not known. The problem is that the loads that occur cannot be predicted when it comes to dimensioning of gearboxes and bearings. As the wind turbines get larger the challenges get so as well. The industry also has to consider low loads. Undesired loads in bearings can be the cause of a total bearing failure.

As a result of the challenge with loads bearing manufacturers now struggle with demands put on them by the rest of the industry. It is not possible to guarantee absolute probability when it comes to load variation. High loads demand larger bearings, which are more sensitive to low loads. It is clear that a clearer knowing is needed for loads and their variations.

Many of today's turbine designs make it expensive to exchange bearings [39]. New designs with new easier exchange periods can keep the costs down. Siemens already has shown that they can retrofit bearings in offshore turbines today. It's a solution costumers have demanded for a long time.

Challenges in the wind power industry are tough and especially when it comes to design of gearboxes. Respect for wind power industry has increased considerably. “To make gearboxes for wind turbines is at the moment beyond our competence, it had been better if we could design and the manufacturer built the gearboxes” says Vincent Schelling of GE Energy. The company has put down large resources on understanding what is demanded of a gearbox in a wind turbine and what could go wrong. There is much more documentation than before. GE doesn't follow the line that many of the competitors does, that is to get a smaller machinery weight and thereby minimize the cost [40].

Most of wind turbine manufacturer have contacts with many different suppliers of gearboxes to secure against failure. The two largest gearbox suppliers are German Winergy and Belgian Hansen. Winergy supplies several suppliers with gearboxes while Hansen only supplies Gamesa and Vestas.

In the same way as wind turbine manufacturers have several contacts with suppliers of gearboxes the suppliers of gearboxes have several contacts with bearing suppliers. The largest supplier of bearings is Swedish SKF [33]. Then comes German INA/FAG closed followed by American Timken.

Ever since the wind power industry had a lot of failure on gearboxes and bearings in the late 90's one has wondered if this could happen again among today's larger wind turbines. So far there has been no repetition of this event. But other problems related to gearboxes and bearings have occurred among the larger machinery.

For Siemens two problems have occurred with bearings on the larger machinery but they are not the same as for smaller machinery [34]. A problem is that bearings skate. Skating is a well known phenomena which occurs when the stress on the bearings are so light that the bearing does not roll. This can lead to damage on the roller paths. This phenomenon should occur on all wind turbines but that has not been the case. The other problem was that a bearing suffered from micro-pitting of the end surface and this led to the geometry changed. This problem was solved by installing a bearing that were practically identical but had a better geometry that reduced the pressure. Inbuilt condition monitoring in each turbine is used to see when damage occur and to make fast repair possible. This was the first real test of the value with condition monitoring. The cost for the system has long ago paid for itself.

2.6 Life Cycle Cost, LCC

Life Cycle Cost (LCC) is an economical calculation method to calculate the total cost for a technical system during its life time. The goal is to minimize the total lifetime cost [41].

The total cost involves costs from planning, purchase, operation and maintenance, to liquidation. For a power plant the costs could typically be investment cost, maintenance cost, down time cost and remainder value. Within this study it has been assumed that the total cost LCC are defined by;

$$LCC = C_{Inv} + C_{CM} + C_{PM} + C_{PL} + C_{Rem} \quad [\text{Euro}] \quad (2.10)$$

where C_{Inv} is the cost for the investment, C_{CM} is the cost for corrective maintenance, C_{PM} is the cost for preventive maintenance, C_{PL} is the cost for production loss and C_{Rem} is the cost for remainder value.

The Present Value Method is used to compare all future payments over a certain time at one point in time, the present time. The present value (PV) means the amount of money that should be put into the bank now at a certain rate (d) to pay for an outlay (C) after n years. This means that all future payments are re-calculated to the equivalent value for the present time.

The present value of one outlay (C) to be paid after n years is gained by multiplying this with the *present value factor* ($PV_f(n,d)$) as follows [28]:

$$PV = C \cdot PV_f(n,d) \Leftrightarrow C \cdot (1+d)^{-n} \quad [\text{Euro}] \quad (2.11)$$

where C is the outlay in [Euro], n is the number of years from the present to the date of the outlay, and d is the discount rate where for example an discount rate of 7 % gives $d = 0.07$.

2.7 Discussion

Definitions that are of special significance for the further analyses are availability, different kinds of maintenance, RCM and condition monitoring. When a CMS is used to plan the maintenance in a better way scheduled maintenance within preventive maintenance becomes condition based maintenance. It is also assumed that there is a change in the corrective maintenance.

RCM has not yet been used as a tool in wind power in Sweden [1], nor Denmark [2]. This is however a possible solution for the wind power industry. In Norway a RCM has been carried out by Vestas [3]. And German Nordex already has Reliability oriented maintenance as a part of their CMS systems [30].

In a report from 1987 P J Quinlan [42] describes RCM and applies it to an example wind farm. This means that RCM in wind farms was an idea long ago. The similarity between aircraft and wind power is stressed. They both demand maintenance of large numbers of similar, high technology equipment. For both groups the cost of labor and equipment is costly, and loss of incomes due to downtime can be significant. The study was carried out with data from actual wind farms in the USA. The results of the application of RCM are a cost-effective scheduled maintenance program combined with an effective equipment-monitoring program for the wind farm. To be able to collect the data that is needed for the RCM analysis some kind of monitoring system is needed, this is where condition monitoring systems, CMS, comes in as a formidable tool. SKF has long experience from RCM through its subsidiary in Scotland [4]. Here both SKF's own CMS system WindCon [17] and other systems are used.

Condition Monitoring is a tool that can be used in several ways among others as vibration analysis and oil analysis. In these two different analyses there are several methods that can be used. When it comes to other energy sources such as nuclear- and hydropower several programs have been developed to handle results from CMS systems in integration with maintenance management systems.

When it comes to wind power the components of interest of condition monitoring are the gearbox, generator and the main shaft. The component of most interest and that seems to be a source of many failures is the gearbox. The gearbox consists of several bearings and gears that can be measured with vibration analysis and to function well it must also have some form of lubrication and therefore oil analysis must also be performed.

One must think of all the aspects in the design of the gearbox. CMS should be integrated at an early stage. How the CMS should be integrated with maintenance programs is the further

question and recommendations for users on how to perform the maintenance with help of CMS is what should be accomplished.

Life Cycle Cost (LCC) is an economical calculation method to calculate a total cost for a technical system during its life length. The goal is to minimize the total lifetime cost. The total cost involves costs from planning, purchase, operation and maintenance to liquidation. For a power plant the costs are e.g. investment cost, operation cost, maintenance cost, down time cost and remainder value. A LCC analysis where the affect of a CMS system is presented in different maintenance strategies is later on presented.

3 Operation and maintenance at three different companies

This section present how the operation and maintenance is performed by three different companies.

1. By Vattenfall at Näsudden, Gotland, with about 30 wind turbines of different manufacturers.
2. By Elsam in Denmark and the UK with for example Horns Rev, the largest offshore farm in the world, and Kentish Flats a wind farm with 30 turbines.
3. By Statkraft at Smöla wind farm in Norway with 68 turbines, the largest farm on land in Europe.

The following description of the maintenance process is based on communication with Anders Andersson; Operation Manager at Vattenfall, Näsudden [1], with Torben K. Hansen; Project Team Manager at Kentish Flats for Elsam [2] and with Arild Soleim; Maintenance Manager at Smöla Wind Farm for Statkraft [3]. Below follows a description of the different companies according; number of turbines and capacity, service contracts, periodic maintenance, manuals and CMS installed.

3.1 Number of turbines and capacity

At Näsudden, Gotland more than 100 wind turbines are installed, owned by different companies. Vattenfall owns about 30 wind turbines of different manufacturers. Some of the turbines at Näsudden are part of research projects and are prototypes. Vattenfall also has wind turbines on other places in Sweden like on the West Coast and one in Lappland.

Elsam operates several turbines and farms in Denmark, like for example Horns Rev the largest offshore wind farm in the world for the moment with 80 turbines of a total output of up to 160 MW. Elsam has also taken over the operation of Kentish Flats an offshore farm with 30x3 MW turbines placed in the North Sea, UK. Kentish Flats is a rather new offshore farm and was completed in September 2005. Elsam also operates Ryå, a farm on land with 5 turbines and a total output of up to 7,5 MW. The main part of Elsams wind turbines in Denmark are in the summer of 2006 taken over by Vattenfall.

Smöla is an island placed in the archipelago outside of Trondheim. The wind farm Smöla was built in two parts, the first part was opened in 2002 and the other part was opened in 2005. The farm has totally 68 turbines and is the largest wind farm on land in Europe. Statkraft operates the older part on their own and Siemens operates part two. Smöla is the largest wind farm on land in Europe with a total capacity of 150 MW.

3.2 Service contracts

Vattenfall has contracts on service with several companies. They have service contracts with Vestas, Siemens and Enercon. Service contracts are valid a year at the time and the choice has been made to not have any insurances for the turbines.

For all new farms within Elsam a 5 year contract with full service is signed with the manufacturer. This is in line with the 5 year warranty period on the wind turbines. For Kentish Flats a five year contract is signed with Vestas.

On the older part Smöla1 Statkraft operates the service on their own. At Smöla a 5 years contract on service is signed with Siemens on the newer part 2.

3.3 Periodic Maintenance

By Vattenfall periodic maintenance is done approximately twice a year. The maintenance can be minor or major. A minor maintenance takes about 4 hours for two people and a major about 7 hours for two people. One hour costs about 540 SEK, that is the cost for a service man from Vestas per hour.

For older smaller turbines the periodic maintenance by Elsam is carried out with 3 months to half a year intervals. Newer, larger turbines have half a year to a year intervals. Older turbines are taken care of by Elsam's own service division Elsam Vind Service with 10 to 15 workers. For larger tasks Elsam rents external independent services.

Scheduled- and unscheduled maintenance is being carried out.

- Scheduled maintenance is lubrication, after tensing of bolts, exchange of filters and check of security equipment.
- Unscheduled maintenance could be anything from banal programming failures and adjustment of relays to bad quality of sensors and failure of blades, generator and gearbox. Experience is here limited.

At Kentish Flats periodic maintenance require two people for two days per turbine and year. All at a cost of 750 EURO per person and day if it is scheduled service and a cost of 850 EURO per person and day if it is major overhaul. These costs includes all associated costs of having the labour i.e. education, safety equipment, pension, offices, transport etc.

On Smöla1 where Statkraft operates the service maintenance is carried out as once a year and twice a year service, often when the production is low. The service once a year is on 50 man hours and costs about 10 000-20 000 NKR. The service twice a year takes about 24 man hours and costs about 5 000-10 0000 NKR. Once a year oil samples are taken and manual inspection and change of filter is performed. On the older part Smöla1 3 people work with operation and maintenance at a cost of 450 NKR per hour.

3.4 Manuals

For the service there is a special manual for Vattenfall where the maintenance is explained carefully by Vestas [43]. The manual contains everything from rules in general and for safety to change of oil filters and control of leakage.

For scheduled maintenance there is a manual that is followed by Elsam when maintenance is carried out. Manuals are often of varying, and sometimes bad, quality and therefore interest groups in Germany now wants to set up directions for maintenance manuals.

At Smöla the following maintenance manual is used for periodic maintenance;

1. Leakage control on gear, oilpump, oilcoler, filters, fittings and hose.
2. Inspection on gear.
3. Control of oillevel on gear.
4. Gear oil tests are taken.
5. Gear oil are changed.
6. Change of filterelements – air filter on gear.
7. Change of filterelements – on-line filter gear.
8. Change of filterelements – off-line
9. Test of pressostate on gear.
10. Control of gear oil coler. (Leakage, cracks)
11. Cleaning of coler outside.
12. Gear oil hoses in rubber are changed.
13. Gear oil hoses in termoplastic are changed.
14. Inspection and cleaning of colefilters on on-line filters.

3.5 Installed CMS

At Näsudden(Vattenfall) one turbine Olsvenne2, a Vestas V90, has a CMS developed by Vestas called VCMS [17]. This is a prototype and data from this system cannot be seen by the personnel of Vattenfall only by Vestas.

On Elsam's onshore farm Ryå a Gram and Juhl's CMS [17] is installed. On the offshore farm Horns Rev Vestas own CMS system VCMS [17] has been installed and is to be installed even on Kentish Flats in the summer of 2006. Here Elsam has access to data from the CMS [2].

At Smöla a vibration monitoring program has been installed at gearboxes and main shaft but this is not in use for the moment. A computer system watches the whole farm online and an alarm is triggered if there is something wrong with the single turbine. When it comes to CMS, Gram and Juhl's CMS [17] is installed at Smöla2 and works well according to the staff. On Smöla2 data from the CMS is only available by Siemens.

3.6 Similarities and differences

In the table below similarities and differences of three wind farms are listed. The three farms are listed according to; number of turbines, CMS installed, if the company has access to data or not, how often periodic maintenance is carried out and valid time on service contracts. The three farms are presented because they are three different parks; one on land (Smöla), one offshore (Kentish Flats) and one with different manufacturers (Näsudden).

Table 3.1 Similarities and differences of three wind farms, sources [1], [2], [3].

System	Number of turbines	CMS	Access to data	Periodic maintenance	Contract on service
1.Näsudden/ Vattenfall	30 of different manufacturers	VCMS*on Olsvenne2	No	With half a year interval	1 year
2.Kentish Flats/ Elsam	30 Vestas	VCMS*	Yes	With half a year interval	5 years with Vestas
3.Smöla/ Statkraft	68 Siemens	Gram and Juhl's CMS	No	With half a year interval	5 years with Siemens (only on part 2)

*Vestas CMS.

4 Life Cycle Cost Analysis

In this study the total cost, LCC , is compared for different alternative maintenance strategies. These strategies are based on our implementing of a CMS to a turbine onshore and a farm offshore and see how this affects different costs within the total cost

$$LCC = C_{Inv} + C_{CM} + C_{PM} + C_{PL} + C_{Rem}$$

At first three strategies where the preventive- and corrective maintenance is affected are presented. Then two strategies where only the corrective maintenance is affected are presented and finally a strategy where only the production loss is affected is presented. The three final strategies are only carried out for the farm offshore while the three first strategies are carried out both for the farm offshore, where an average turbine is observed, and the single turbine onshore. The following strategies are based on assumptions.

1. In strategy 1 the cost for preventive maintenance is compared to the cost for preventive maintenance and a CMS. The cost for corrective maintenance and the cost for production loss are set to zero.
2. In strategy 2 the cost for preventive- and corrective maintenance is compared to the cost for preventive- and corrective maintenance and a CMS. The cost for production loss is set to zero.
3. In strategy 3 the cost for preventive- and corrective maintenance is compared to the cost for preventive maintenance, when corrective maintenance is set to zero, and a CMS. The cost for production loss is also set to zero.
4. In strategy 4 the man days are reduced and corrective maintenance becomes preventive because of better planning with CMS. The point where a certain amount of unscheduled maintenance becomes preventive is found to see when CMS is profitable.
5. In strategy 5 the man days within the cost for major components replacements are reduced when the components are replaced two at a time instead of one at a time.
6. In strategy 6 the availability increases and the cost for production loss is thereby decreased.

The purposes of these strategies are to see if a CMS is profitable. In the three first strategies a percentage of how much the cost must be decreased to make CMS profitable is calculated. The three final strategies give a direct indication of whether the price of CMS is covered within the strategy.

4.1 Method

The sum of the costs for each year LCC is calculated and multiplied with the *present value factor* ($PV_f(n,d)$). This gives the present value for the sum of costs LCC , $PV(LCC)$ for each year which then is summarized over the years into the total sum of present value for the cost LCC , $TPV(LCC)$. This is first done without a CMS and is then called the basic case.

The cost for CMS is then added and the effect of different strategies is calculated. First in three strategies where one wind turbine onshore versus one average wind turbine offshore is observed. Then one wind farm offshore where the maintenance is planned using CMS is observed. At last conclusions on possible benefits of using CMS is drawn.

When a CMS is implemented we assume that we could get less scheduled maintenance and more condition based maintenance both within the preventive maintenance. We also assume that we get less corrective maintenance. The cost for a CMS is a part of the cost for preventive maintenance C_{PM} . The cost for replacements of major components is a part of the cost for corrective maintenance C_{CM} .

The cost for preventive maintenance C_{PM} could be divided into a cost for a CMS, C_{CMS} , and a cost for scheduled service, C_S . That is $C_{PM} = C_{CMS} + C_S$.

The cost for preventive- and corrective maintenance and a CMS is $C_{PM} + C_{CM}$, that is $C_{CMS} + C_S + C_{CM}$.

To compare *LCC* in different cases with a cost for CMS three strategies are presented. These are:

1. C_{CM} and C_{PL} are set to zero and C_{PM} is decreased so that TPV for the decreased C_{PM} with a CMS equals TPV of C_{PM} without a CMS.
That is $TPV(C_{CMS} + A_1 \cdot C_S) = TPV(C_S)$ where A_1 is a factor that decreases C_S .
2. C_{PL} is set to zero and $C_{PM} + C_{CM}$ is decreased so that TPV for the decreased $C_{PM} + C_{CM}$ with a CMS equals TPV of $C_{PM} + C_{CM}$ without a CMS.
That is $TPV(C_{CMS} + A_2 \cdot (C_S + C_{CM})) = TPV(C_S + C_{CM})$ where A_2 is a factor that decreases $C_S + C_{CM}$.
3. C_{PL} is set to zero and C_{CM} is at first set to zero so that C_S within C_{PM} with a CMS can be increased so that TPV of an increased C_S within C_{PM} with a CMS equals TPV of $C_{PM} + C_{CM}$ without a CMS.
That is $TPV(C_{CMS} + A_3 \cdot C_S) = TPV(C_S + C_{CM})$ where A_3 is a factor that increases C_S .

C_{CM} can be divided into a cost for unscheduled service C_{US} and a cost for replacements of major components C_{MC} , that is $C_{CM} = C_{US} + C_{MC}$.

C_{US} can be divided into a cost for man days C_M and a cost for spare parts C_{SP} , that is $C_{US} = kC_M + C_{SP}$, where k is the number of man days.

C_{MC} can be divided into a cost for man days C_M and a cost for replacements of major components C_R , that is $C_{MC} = kC_M + C_R$, where k is the number of man days.

To compare C_{CM} for different scenarios another two strategies where the man days are affected are here presented. These are:

4. In C_{US} , kC_M is decreased because the man days can be reduced within the unscheduled service when we plan it better with CMS. Unscheduled service becomes

preventive. The point B_1 where a certain amount of unscheduled service becomes preventive is found to be where CMS is profitable.

$$C_{US} = kC_{M,US} + C_{SP} \text{ becomes } C_{US} = kC_{M,S} + C_{SP}$$

5. The major components are replaced two at a time instead of one at a time because of CMS. This means that in C_{MC} , k becomes $k/2$ and kC_M becomes $\frac{k}{2}C_M$.

$$C_{MC} = kC_M + C_R \text{ becomes } C_{MC} = \frac{k}{2}C_M + C_R.$$

To see how CMS affects the production loss a final strategy where the availability increases is here presented:

6. If the availability increases into B_2 from 97,5% , because of CMS the total sum of the present value of the cost increases with $TPV(LCC)_{\text{Before}} - TPV(LCC)_{\text{After}}$.

4.2 Application

The method has been applied for two different studies, one study with a single wind turbine onshore and one study with a wind farm with 30 turbines offshore. The single turbine is a Vestas V90, that is a 3 MW turbine. The farm consists of 30x3 MW Vestas V90.

At Näsudden on Gotland a Vestas V90 named Olsvenne2 is placed. This turbine is equipped with a CMS system but this is for now not used to plan the maintenance in any way. On Kentish Flats in the UK Danish Elsam operates a farm with 30x3 MW turbines. Vestas VCMS [17] is here to be installed in the summer of 2006.

The analyses have been made on estimations on the costs for the single turbine onshore [1] and the farm offshore [2]. The task to estimate costs is difficult especially as prices vary a lot. For cost of different major components see Table 4.1. The investment cost for one CMS is 20 000 Euro [5].

Table 4.1 Cost for replacements of major components, source [1], [2].

Component	Cost [Euro]
Gearbox	300 000
Generator	150 000
Transformer	100 000
Blade	200 000

A present value of the total cost LCC for every year has been calculated and the total sum of all present values has been calculated into the total sum of the present value of LCC . The discount rate d is first set to 7 percent and the life length of a turbine N is 20 years. The discount rate has then been changed to 0 % and 10 % respectively, and the sum of the present value has been calculated. Statistics from Finland on how major components are replaced were used to see how the cost changes.

In the six strategies with a CMS the total sum of the present value of LCC is calculated for different scenarios. In strategy 1 the preventive maintenance must decrease with A_1 to make CMS profitable. In strategy 2 the preventive and corrective maintenance must decrease with A_2 together to make CMS profitable. In strategy 3 the preventive maintenance with CMS could increase with A_3 when corrective maintenance is zero because of CMS.

Some benefits with CMS are that maintenance could be planned better, the right service can be carried out at the right time and unnecessary replacements can be minimized [10]. Downtime could be reduced as failures are discovered easier. The costs that can be saved with CMS are e.g. costs for transportation to a wind farm offshore. Repairs can be planned in a new way. If one gearbox need repair then another gearbox that might go down in a later stage could be repaired at the same time thanks to the information that the CMS gives. This saves money for e.g. transportation. On Kentish Flats it is hoped that the installation of CMS after a certain period of teaching time should allow that both scheduled and unscheduled service could be optimized [2]. Here especially replacements of major components are of interest. The cost for a man day includes all associated costs of having the labour i.e. education, safety equipment, pension, offices, transport etc. In the two strategies where man days are reduced at the farm because of better planning with a CMS the difference in the total sum of the present value of LCC before and after is calculated.

In strategy 4 the cost for man days kC_M is decreased as unscheduled service becomes preventive, that is the cost for man days decreases from 1000 Euro per man day into 750 Euro per man day. The point B_1 where a certain amount of unscheduled maintenance becomes preventive is found to see where CMS is profitable. In the strategy 5 major components are replaced two at a time and this means that the man days k is reduced into $k/2$ within the cost for replacements C_{MC} . In the final strategy 6 where production loss is affected the availability increases into B_2 . The cost for production loss is thereby decreased.

For strategy 4 to 6 the discount rate has then been changed to zero and 10 % respectively, and the difference in the total sum of the present value, LCC , has been calculated. This gives a direct information of if the strategy covers the cost for CMS.

4.3 Input data for Olsvenne2

The investment cost comes in year zero. Connection cost is within the investment cost. Preventive and corrective maintenance are within the investment cost for two years. There is also a cost for consumption materials in these two years. These costs come in as costs in the preventive maintenance C_{PM} and the corrective maintenance C_{CM} for year one and two, see Table 4.2. Costs for preventive maintenance C_{PM} and corrective maintenance C_{CM} from year three are estimated for each year see Table 4.2.

A cost for production loss has been calculated as the income times the unavailability from year one and is here called C_{PL} . Here the commercial availability has been used, that is 97,5%. The unavailability is calculated as $1 - \text{availability}$. A cost for demolition and recycling has been estimated for the last year called Rem see Table 4.2.

Costs for major component replacements have been calculated from the failure rate used in the Kentish Flats calculation and from the failure rate of the gearbox. The gearbox is to be changed twice during a lifetime. The generator is to be changed once during a lifetime.

Transformer and blade are to be changed 1/10 time during a lifetime. These costs are put together as C_R , cost for replacements, according to Equation (4.1).

$$C_R = C_{R,GB} + C_{R,G} + C_{R,T} + C_{R,B} \quad (4.1)$$

where $C_{R,GB}$ is the cost for replacements of gearboxes for a year,
 $C_{R,G}$ is the cost for replacements of generators for a year,
 $C_{R,T}$ is the cost for replacements of transformers for a year
and $C_{R,B}$ is the cost for replacements of blades for a year.

For costs placed in the different years see Table 4.2 for replacements every year. Here the same frequency of how often replacements are made and costs as in the Kentish Flats study has been used besides the failure rate of the gearbox that is the actual failure rate on Olsvenne2.

The same thing has been done using data from Finland on how often the replacements are made. See Table 4.4 with calculations.

The investment cost in one CMS is C_{CMS} in year zero. $C_{CMS} = 20\,000$ Euro.

Input data

In the table below Investment indicates the investment cost, C_{PM} the cost for preventive maintenance, C_{CM} the cost for corrective maintenance, C_R the costs for replacements; observe that this cost also is within the corrective maintenance. C_{PL} indicates cost for production loss, Rem is the remainder value and Sum is the sum of all costs. The input data in the table is without a CMS and for one single turbine.

Table 4.2 Input data as replacements of major component, made every year for Olsvenne2, source [1], [2].

Time [year]	Investment [Euro/year]	C_{PM} [Euro/year]	C_{CM} [Euro/year]	C_{PL} [Euro/year]	C_R [Euro/year]	Rem [Euro/year]	Sum [Euro/year]
0	3000000	0	0	0	0	0	3000000
1	0	1500	1500	11000	39000	0	53000
2	0	1500	1500	11000	39000	0	53000
3	0	10000	8000	11000	39000	0	68000
.							
.							
19	0	10000	8000	11000	39000	0	68000
20	0	10000	8000	11000	39000	100000	168000

4.4 Input data for Kentish flats

Cost for the first year is investment cost including among other things connection cost. From year 1 to 20 costs for scheduled service come in and are the same every year. Major overhaul

is included in scheduled service most years but comes in as a cost in the years 4, 6, 9, 13 and 14. This is included in the preventive maintenance cost C_{PM} .

The unscheduled service costs decrease from year one for four years and increase in the end and include one visit to each turbine per month in year one, reduced to one visit per three months in year four. This is included in the corrective maintenance cost C_{CM} . A cost for production loss has been calculated as the income times the unavailability from year one, C_{PL} . Here the commercial availability has been used, that is 97,5%. The unavailability is calculated as $1 - \text{availability}$. These costs are calculated together as costs for preventive maintenance C_{PM} , corrective maintenance C_{CM} , and cost for production loss C_{PL} see Table 4.3 where also investment cost and costs for replacements of major components C_R which is a part of the corrective maintenance are included.

The major component replacements have been estimated per year for 20 years. For example are 17 gearboxes to be replaced of 30 during the lifetime. 20 generators are to be replaced during the lifetime. 3 transformers and 3 blades are to be replaced of 30 during the lifetime. These costs are put together as C_R , cost for replacements according to Equation (4.1) and are a part of the cost for corrective maintenance C_{CM} . For costs the different years see Table 4.3 for replacements put in every year according to Kentish Flats.

$$C_R = C_{R,GB} + C_{R,G} + C_{R,T} + C_{R,B} \quad (4.1)$$

where $C_{R,GB}$ is the cost for replacements of gearboxes for a year,
 $C_{R,G}$ is the cost for replacements of generators for a year,
 $C_{R,T}$ is the cost for replacements of transformers for a year
and $C_{R,B}$ is the cost for replacements of blades for a year.

The same thing has been done using data from Finland on how often the replacements are performed. See Table 4.4 with calculations.

The investment cost in 30 CMS is $30C_{CMS}$ in year zero. $30C_{CMS} = 600\,000$ Euro.

One scheduled man day costs 750 Euro at Kentish Flats $C_{M,S} = 750$ Euro.

One unscheduled man day costs 1000 Euro at Kentish Flats. $C_{M,US} = 1000$ Euro.

The number of man days k is 43; this means that 43 components are replaced in 43 days. 17 gearboxes, 20 generators, 3 transformers and 3 blades make 43 components to be replaced during the wind farm life time.

Input data

In the table below Investment indicates the investment cost, C_{PM} the cost for preventive maintenance, C_{CM} the cost for corrective maintenance, C_R the cost for replacements, observe that this cost also is within the corrective maintenance. C_{PL} indicates cost for production loss and Sum is the sum of all costs. The input data in the table is without a CMS for the entire farm.

Table 4. 3 Input data as replacements of major components; made every year for Kentish Flats, source [2].

Time [year]	Investment [Euro/year]	C_{PM} [Euro/year]	C_{CM} [Euro/year]	C_R [Euro/year]	C_{PL} [Euro/year]	Sum [Euro/year]
0	100000000	0	0	0	0	100000000
1	0	485000	1650000	450000	330000	2508000
2	0	605000	1350000	450000	330000	2328000
3	0	485000	1110000	450000	330000	1968000
4	0	2115000	927600	450000	330000	3415600
5	0	605000	927600	450000	330000	1905600
6	0	2129000	927600	450000	330000	3429600
7	0	485000	927600	450000	330000	1785600
8	0	605000	927600	450000	330000	1905600
9	0	6870000	927600	450000	330000	8170600
10	0	485000	927600	450000	330000	1785600
11	0	605000	927600	450000	330000	1905600
12	0	485000	927600	450000	330000	1785600
13	0	2204000	927600	450000	330000	3504600
14	0	2235000	927600	450000	330000	3535600
15	0	485000	927600	450000	330000	1785600
16	0	485000	927600	450000	330000	1785600
17	0	605000	927600	450000	330000	1905600
18	0	485000	1170000	450000	330000	2028000
19	0	485000	1350000	450000	330000	2208000
20	0	485000	1350000	450000	330000	2208000

4.5 Input data from replacements according to Finnish statistics

The Finnish statistics are based on failures on the 92 wind turbines in Finland for the years 2000-2004. When statistics from Finland were used on how replacements of major components were performed the costs that change were C_R , that is the costs for replacements. Table 4.4 shows replacements on Olsvenne2 and Kentish Flats as replacements are carried out every year. Input data for replacements of components are shown for one turbine for Olsvenne2 and for 30 turbines for Kentish Flats. The same prices have been used as in Table 4.1 and the replacement frequency is the same, that is from the Finnish statistics [10]. In 5 years 46 gearboxes of 92 were replaced, 30 generators of 92 were replaced, 38 transformers of 92 were replaced and 70 blades out of 92 were replaced.

$$C_R = C_{R,GB} + C_{R,G} + C_{R,T} + C_{R,B} \quad (4.1)$$

where $C_{R,GB}$ is the cost for replacements of gearboxes for a year,
 $C_{R,G}$ is the cost for replacements of generators for a year,
 $C_{R,T}$ is the cost for replacements of transformers for a year
and $C_{R,B}$ is the cost for replacements of blades for a year.

For example consider the exchange of gearboxes: there were 46 gearboxes replaced out of 92 in 5 years. This gives us $C_{R,GB} = \frac{46}{5 \cdot 92} \cdot 300000 = 30000$ Euro per year in replacement cost for gearboxes.

In the same way we get $C_{R,G} = \frac{30}{5 \cdot 92} \cdot 150000 = 9783$ Euro per year in replacement cost for

generators, and $C_{R,T} = \frac{38}{5 \cdot 92} \cdot 100000 = 8261$ Euro per year in replacement for transformers,

and $C_{R,B} = \frac{70}{5 \cdot 92} \cdot 200000 = 30435$ Euro per year in replacement for blades.

These costs summarized gives us the total cost $C_R = 30\,000 + 9\,783 + 8\,261 + 30\,435 = 78\,478$ Euro for one turbine and $30 \cdot 78478 = 2354300$ for a wind farm with 30 turbines.

Table 4.4 Input data as replacements of major components; made every year for Olsvenne2 and Kentish Flats according to Finnish statistics, source [10].

Time [year]	Olsvenne2 C_R [Euro]	Kentish Flats C_R [Euro]
0	0	0
1	78478	2354300
.		
.		
20	78478	2354300

Input data above is for one single turbine for Olsvenne2 and for an entire farm, that is 30 turbines, for Kentish Flats.

4.6 Results

This chapter presents results from the calculations of the two cases Olsvenne2 and Kentish Flats. For Olsvenne2 the results of the total sum of the present value for the cost LCC , and the strategies 1-3 are presented. For Kentish Flats the results of the total sum of the present value for the cost LCC , and the strategies 1-6 are presented. In strategy 4-6 the man days at the farm are affected by CMS and this gives a change in the cost C_{CM} .

4.6.1 Olsvenne2

The sum of the present value for 20 years, the total sum of the present value for the cost LCC , was about 3,72 million Euro for Olsvenne2 when major parts were changed every year and the discount rate was set to 7%. That is the turbine would cost about 3,72 million Euro. For present value cost every year and preventive maintenance cost (PM), corrective maintenance cost (CM) and cost for replacements see Figure 4.1.

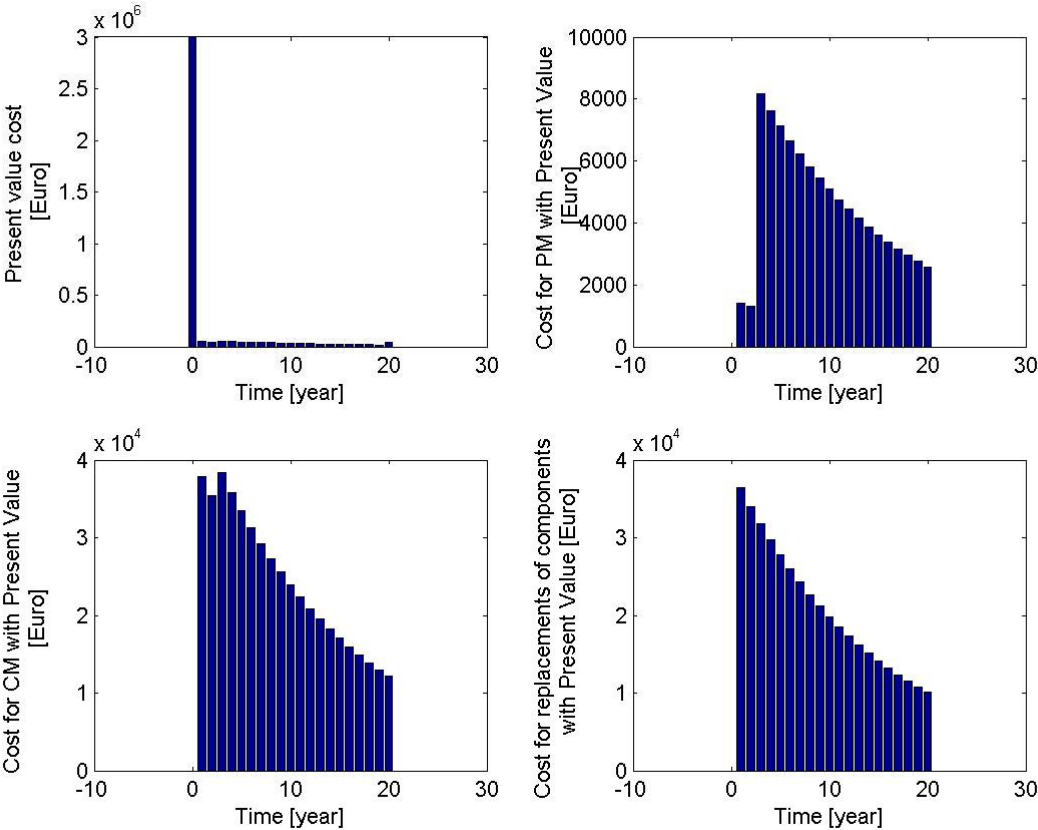


Figure 4.1 Present value cost and costs for preventive maintenance (PM), corrective maintenance (CM) and replacements of major components with replacements every year for Olsvenne2. The cost for replacements of major components is within the corrective maintenance (CM). The discount rate was set to 7%.

For the first two years the cost for consumed materials comes in both in the preventive and corrective maintenance. Then there is a constant cost for preventive and corrective maintenance that decreases because of the present value. The major cost is the investment cost. The major part of the corrective maintenance is replacements of major components.

The results of the strategies 1-3 are presented as follows:

Strategy 1

$$TPV(C_{CMS} + A_1 \cdot C_S) = TPV(C_S)$$

where A_1 is a factor that decreases C_S .

When C_{CM} and C_{PL} are set to zero and C_{PM} is decreased so that TPV for the decreased C_{PM} with a CMS equals TPV of C_{PM} without a CMS the preventive maintenance C_{PM} must be decreased with 23% per year, that is $A_1 = 0,77$.

See Figure 4.2. The total sum of the present value TPV is the same for the right and the left alternative, that is $TPV(C_{CMS} + A_1 \cdot C_S) = TPV(C_S)$.

For the basic case and a CMS the cost for the preventive maintenance must decrease by 23 % to get the LCC of the basic case.

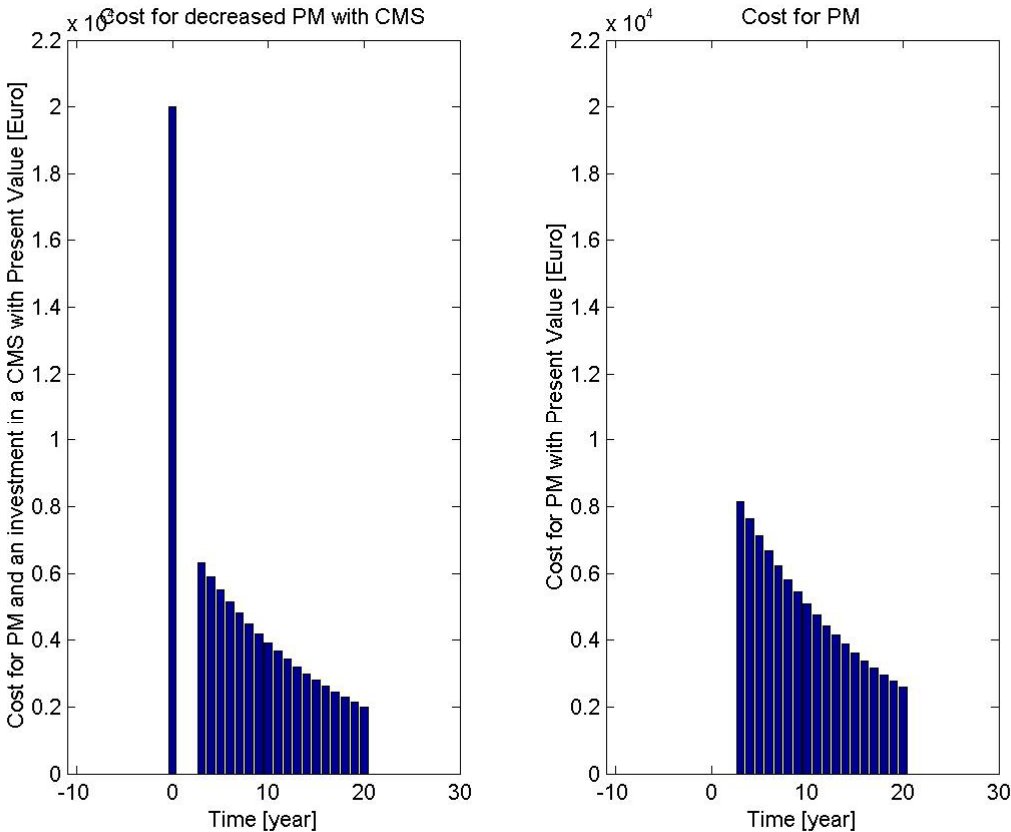


Figure 4.2 Present value cost for a decreased preventive maintenance (PM) with an investment in a CMS compared to the present value cost of the preventive maintenance for Olsvenne2. The discount rate was set to 7%.

Strategy 2

$TPV(C_{CMS} + A_2 \cdot (C_S + C_{CM})) = TPV(C_S + C_{CM})$ where A_2 is a factor that decreases $C_S + C_{CM}$.

When C_{PL} is set to zero and $C_{PM} + C_{CM}$ is decreased so that TPV for the decreased $C_{PM} + C_{CM}$ with a CMS equals TPV of $C_{PM} + C_{CM}$ without a CMS the preventive- and corrective maintenance $C_{PM} + C_{CM}$ must be decreased by 3.5% together per year, that is $A_2 = 0,965$.

See Figure 4.3. The total sum of the present value is the same for the right and the left alternative, that is $TPV(C_{CMS} + A_2 \cdot (C_S + C_{CM})) = TPV(C_S + C_{CM})$.

For the basic case and a CMS the cost for the preventive- and corrective maintenance must decrease by 3,5 % together to get the LCC of the basic case.

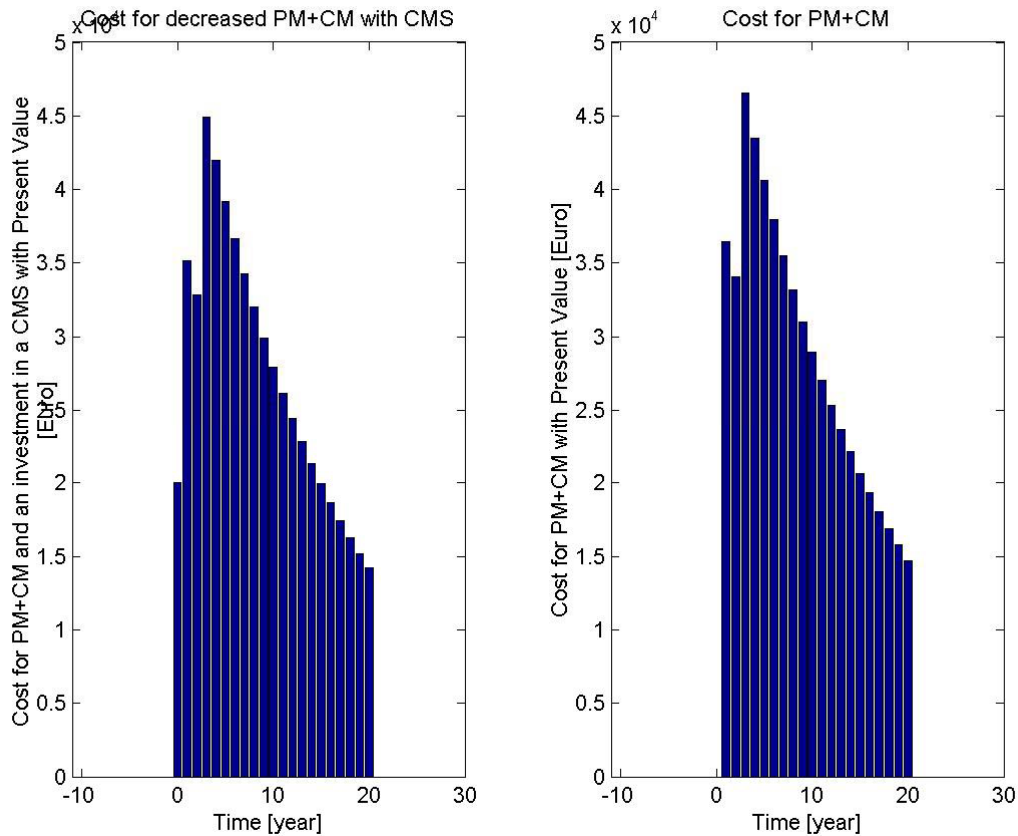


Figure 4.3 Present value cost for a decreased preventive maintenance (PM) and corrective maintenance (CM) with an investment in a CMS compared to the present value cost of the preventive maintenance and corrective maintenance for Olsvenne2. The discount rate was set to 7%.

Strategy 3

$TPV(C_{CMS} + A_3 \cdot C_S) = TPV(C_S + C_{CM})$ where A_3 is a factor that increases C_S .

When C_{PL} is set to zero and C_{CM} is at first set to zero so that C_S within C_{PM} with a CMS can be increased so that TPV of an increased C_S within C_{PM} with a CMS equals TPV of $C_{PM} + C_{CM}$ without a CMS, C_S could increase by 6.27 times per year, that is $A_3 = 6,27$.

See Figure 4.4. The total sum of the present value is the same for the right and the left alternative, that is $TPV(C_{CMS} + A_3 \cdot C_S) = TPV(C_S + C_{CM})$.

For the basic case and a CMS the cost for the preventive maintenance could increase by 6,23 times to get the LCC of the basic case when the cost for corrective maintenance is set to zero.

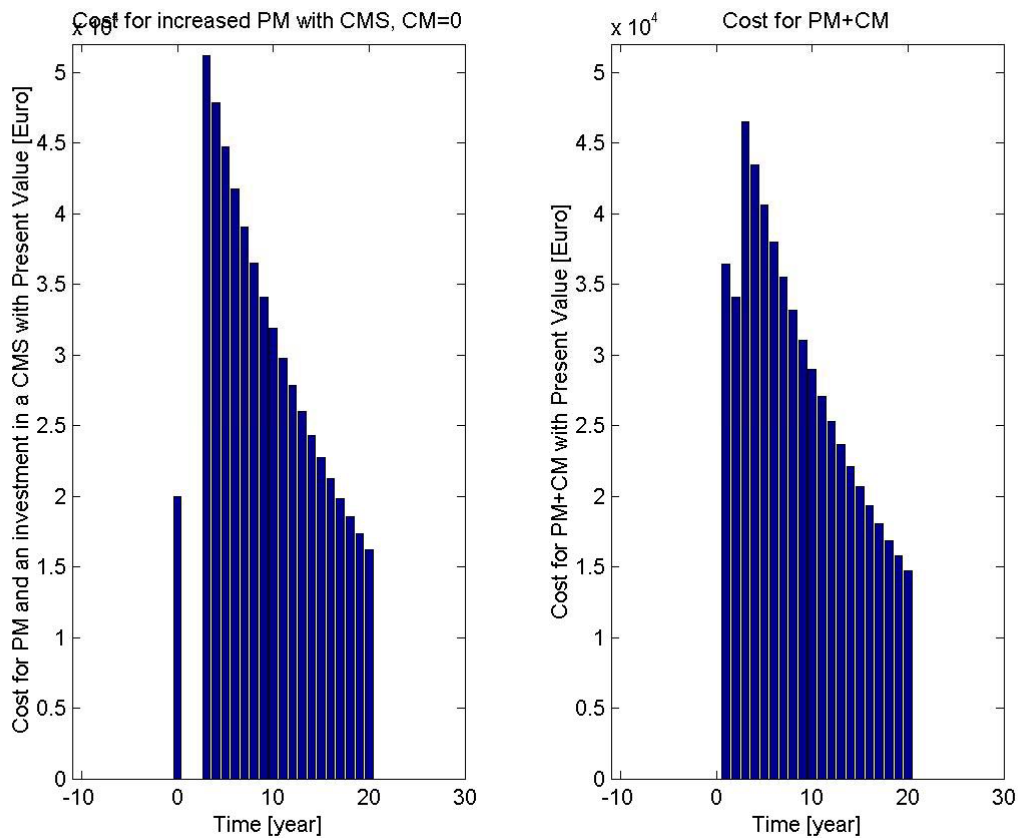


Figure 4.4 Present value cost for an increased preventive maintenance (PM), as the corrective maintenance (CM) is set to zero, with an investment in a CMS compared to the present value cost of the preventive maintenance and corrective maintenance for Olsvenne2. The discount rate was set to 7%.

4.6.2 Kentish Flats

For Kentish Flats Wind Farm the total sum of the present value for the cost *LCC* would be about 4,25 million Euro per turbine with replacements every year and discount rate set to 7 %. For present value cost every year and preventive maintenance cost (PM), corrective maintenance cost (CM) and cost for replacements see Figure 4.5.

Costs for major overhaul are included in the preventive maintenance and the most costs are in year 9 as seen in Figure 4.5. Major costs are also in year 4, 6 and 13, 14. The costs for replacements of major components are included in the corrective maintenance.

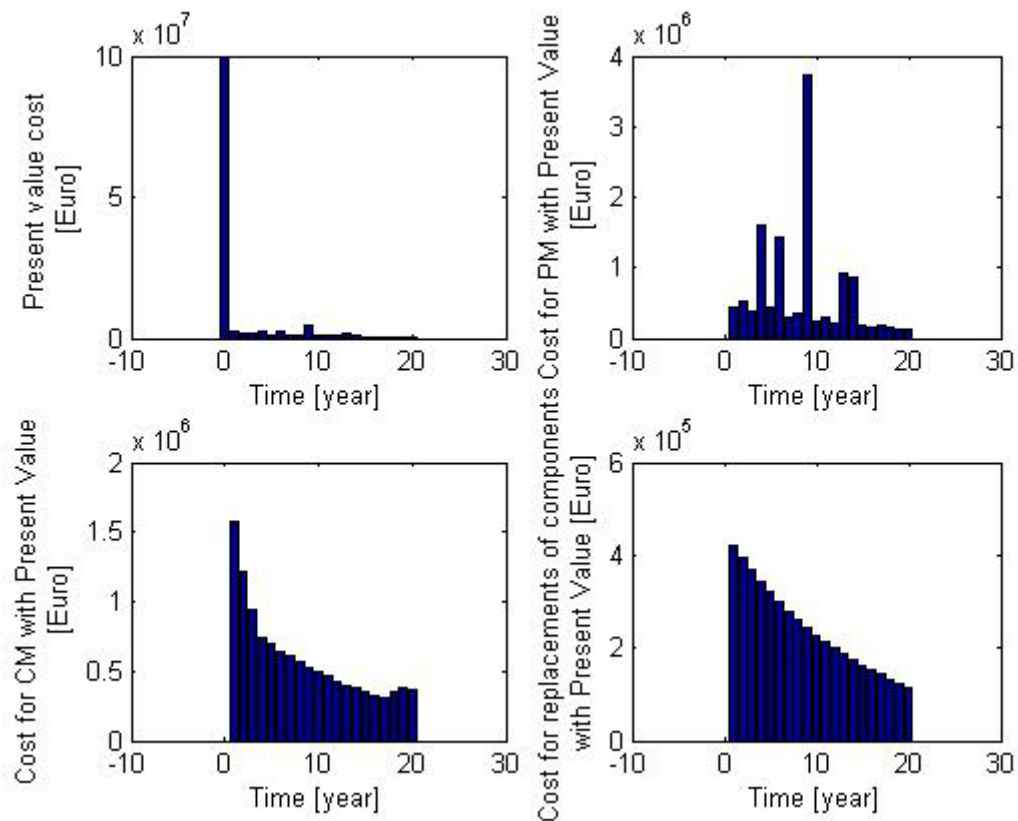


Figure 4.5 Present value cost and costs for preventive maintenance (PM), corrective maintenance (CM) and replacements of major components with replacements every year for Kentish Flats Wind Park. The cost for replacements of major components is within the corrective maintenance (CM). The discount rate was set to 7%.

The results of the strategies 1-6 for Kentish Flats are presented as follows:

Strategy 1

$TPV(C_{CMS} + A_1 \cdot C_S) = TPV(C_S)$ where A_1 is a factor that decreases C_S .

When C_{CM} and C_{PL} are set to zero and C_{PM} is decreased so that TPV for the decreased C_{PM} with a CMS equals TPV of C_{PM} without a CMS the preventive maintenance C_{PM} must be decreased by 4,5 % per year, that is $A_1 = 0,955$.

See Figure 4.6. The total sum of the present value TPV is the same for the right and the left alternative, that is $TPV(C_{CMS} + A_1 \cdot C_S) = TPV(C_S)$.

For the basic case and a CMS the cost for the preventive maintenance must decrease by 4,5 % to get the LCC of the basic case.

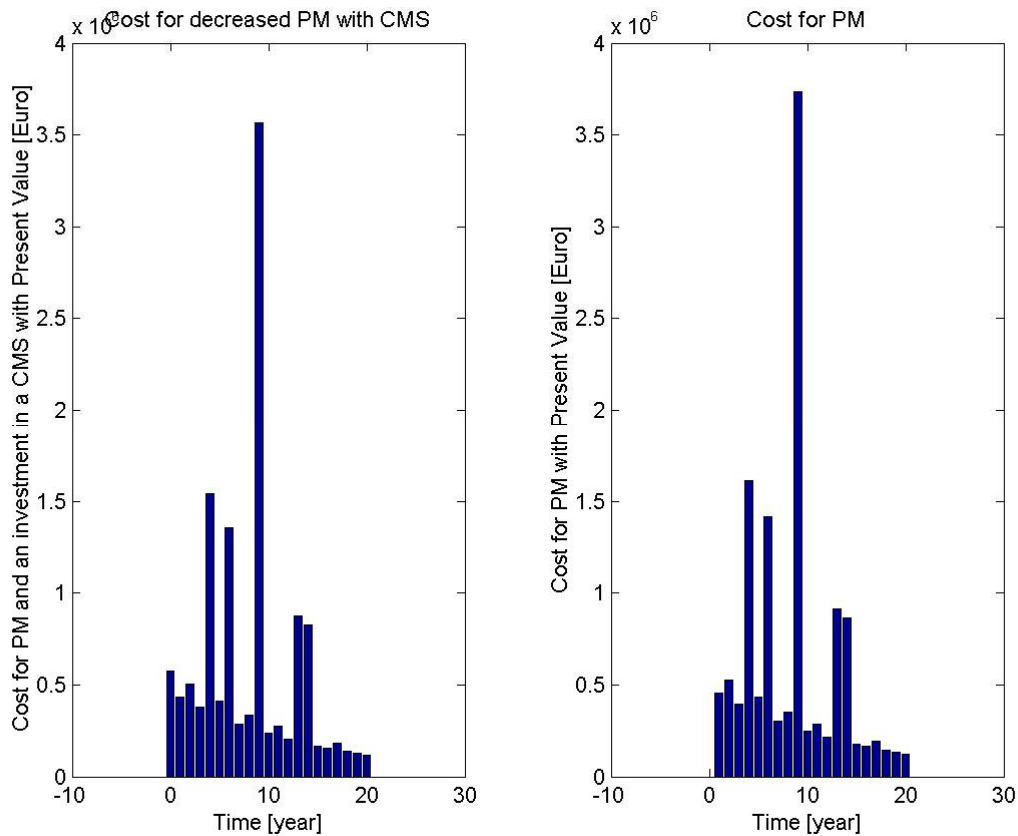


Figure 4.6 Present value cost for a decreased preventive maintenance (PM) with an investment in 30 CMS compared to the present value cost of the preventive maintenance for Kentish Flats. The discount rate was set to 7%.

Strategy 2

$TPV(C_{CMS} + A_2 \cdot (C_S + C_{CM})) = TPV(C_S + C_{CM})$ where A_2 is a factor that decrease $C_S + C_{CM}$.

When C_{PL} is set to zero and $C_{PM} + C_{CM}$ is decreased so that TPV for the decreased $C_{PM} + C_{CM}$ with a CMS equals TPV of $C_{PM} + C_{CM}$ without a CMS the preventive- and corrective maintenance $C_{PM} + C_{CM}$ must be decreased by 2,5% together per year, that is $A_2 = 0,975$.

See Figure 4.7. The total sum of the present value is the same for the right and the left alternative, that is $TPV(C_{CMS} + A_2 \cdot (C_S + C_{CM})) = TPV(C_S + C_{CM})$

For the basic case and a CMS the cost for the preventive- and corrective maintenance must decrease by 2,5 % together to get the *LCC* of the basic case.

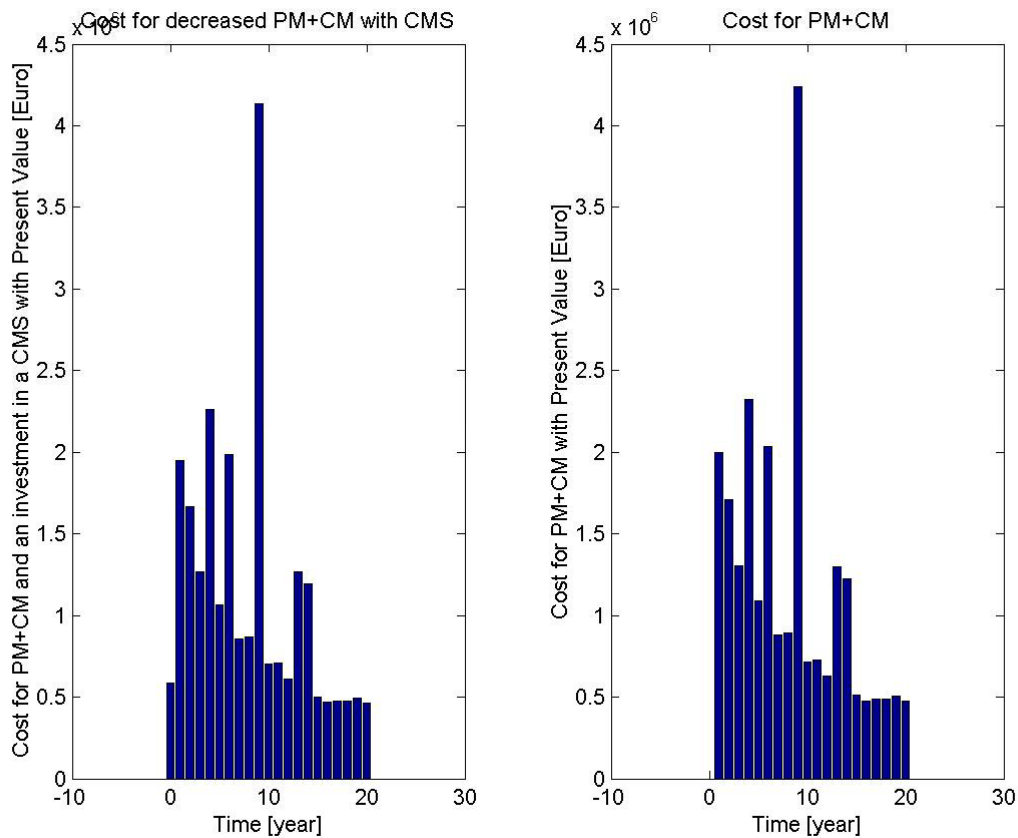


Figure 4.7 Present value cost for a decreased preventive maintenance (PM) and corrective maintenance (CM) with an investment in 30 CMS compared to the present value cost of the preventive maintenance and corrective maintenance for Kentish Flats. The discount rate was set to 7%.

Strategy 3

$TPV(C_{CMS} + A_3 \cdot C_S) = TPV(C_S + C_{CM})$ where A_3 is a factor that increases C_S .

When C_{PL} is set to zero and C_{CM} is at first set to zero so that C_S within C_{PM} with a CMS can be increased so that TPV of an increased C_S within C_{PM} with CMS equals TPV of $C_{PM} + C_{CM}$ without CMS, C_S could increase by 85 % per year, that is $A_3 = 1,85$.

See Figure 4.8. The total sum of the present value is the same for the right and the left alternative, that is $TPV(C_{CMS} + A_3 \cdot C_S) = TPV(C_S + C_{CM})$.

For the basic case and a CMS the cost for the preventive maintenance could increase by 1,85 times to get the LCC of the basic case when the cost for corrective maintenance is set to zero.

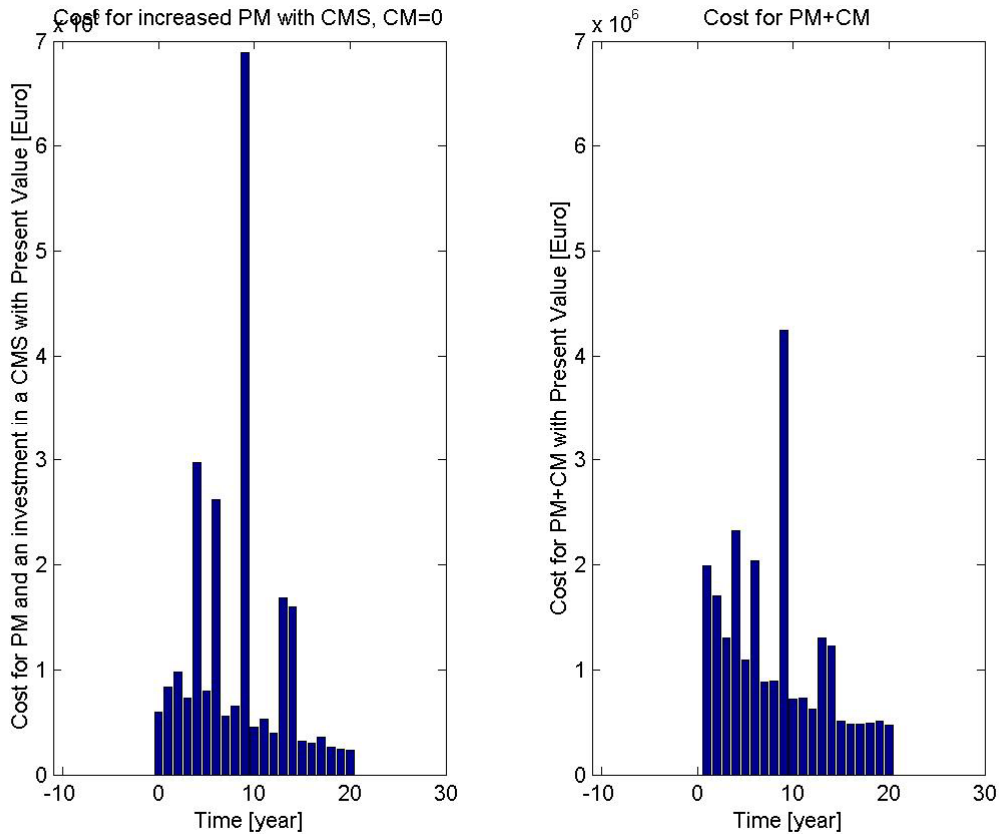


Figure 4.8 Present value cost for an increased preventive maintenance (PM), as the corrective maintenance (CM) is set to zero, with an investment in 30 CMS compared to the present value cost of the preventive maintenance and corrective maintenance for Kentish Flats. The discount rate was set to 7%.

Strategy 4

In C_{US} , kC_M is decreased because the man days can be reduced within the unscheduled service when we plan it better with CMS. Unscheduled service becomes preventive and the cost for unscheduled man days becomes a cost for preventive man days.

$$C_{US} = kC_{M,US} + C_{SP} \text{ becomes } C_{US} = kC_{M,P} + C_{SP}$$

A decrease in kC_M with 5 %, that is a reduction in man days with 5%, which is motivated by better planning with CMS. If B_1 is set to 0,95 and the cost for the man days is changed from unscheduled into preventive maintenance the difference in the total sum of the present value of the cost LCC , $TPV_{\text{Before}}(LCC) - TPV_{\text{After}}(LCC) = 1\,014\,900$ Euro for the entire farm.

If B_1 is set to 1, that is a change in kC_M of 0%, but the cost for the man days is changed from unscheduled into preventive the difference in the total sum of the present value of the cost LCC , $TPV_{\text{Before}}(LCC) - TPV_{\text{After}}(LCC) = 600\,000$ Euro for the entire farm when 47% of the unscheduled maintenance becomes preventive maintenance. This means that when the difference in $TPV(LCC)$ depends on that 47 % of the unscheduled service becoming preventive maintenance, which is cheaper, the difference is the cost for CMS.

Strategy 5

The major components are replaced two at a time instead of one at a time because of CMS.

This means that in C_{MC} , k becomes $k/2$ and kC_M becomes $\frac{k}{2}C_M$.

$$C_{MC} = kC_M + C_R \text{ becomes } C_{MC} = \frac{k}{2}C_M + C_R.$$

As $k = 43$, $k/2 = 21,5$, which means that 43 components are replaced in 21,5 days instead of 43 days. The difference in total sum of the present value of the cost C_{CM} , $TPV_{\text{Before}}(LCC) - TPV_{\text{After}}(LCC) = 227\,770$ Euro for the entire farm.

When k becomes $k/5$, $k/10$, $k/100$, that is the replacements are carried out faster and faster the cost for CMS can not be covered within the reduction in the cost for man days within the cost for replacements of major components.

Strategy 6

If the availability for the entire farm increases into B_2 from 97,5% , the total sum of the present value of the cost increases by $TPV(LCC)_{\text{Before}} - TPV(LCC)_{\text{After}}$.

If B_2 is set to 98 %, the cost for production loss C_{PL} decreases from 330 000 Euro to 264 000 Euro per year and $TPV(LCC)_{\text{Before}} - TPV(LCC)_{\text{After}} = 699\,200$ Euro for the entire farm.

If B_2 is set to 97,929 %, $TPV(LCC)_{\text{Before}} - TPV(LCC)_{\text{After}} = 599\,920$ Euro for the entire farm. That is an increase of a bit more than 0.43 % in the availability makes a CMS profitable.

4.6.3 Replacement data from Finnish statistics

When statistics from Finland on how major components are replaced were used the costs increased. The statistics from Finland are based on the 92 turbines in Finland and are for the years 2000-2004.

For Olsvenne2 the total cost for a turbine, with replacements of major components every year, was 4,14 million Euro. For Kentish Flats the total cost for a turbine, with replacements of major components every year and with the same conditions, was 4,92 million Euro.

How the present value of the costs for the replacements of major components, C_R , every year change when the statistics from Finland are used compared to when the basic case estimation is used could be seen in Figure 4.9. The costs for replacements of major components are twice as high when the statistics from Finland are used compared to when data from the basic case study is used. The costs for replacements of major components are almost the same for Olsvenne2 and Kentish flats, besides from that the cost for Kentish Flats is for 30 turbines and the cost for Olsvenne2 only is for one turbine. Another difference is that the gearbox is replaced according to Olsvenne2 in the basic case for Olsvenne2 and according to Kentish Flats in the Kentish Flats case.

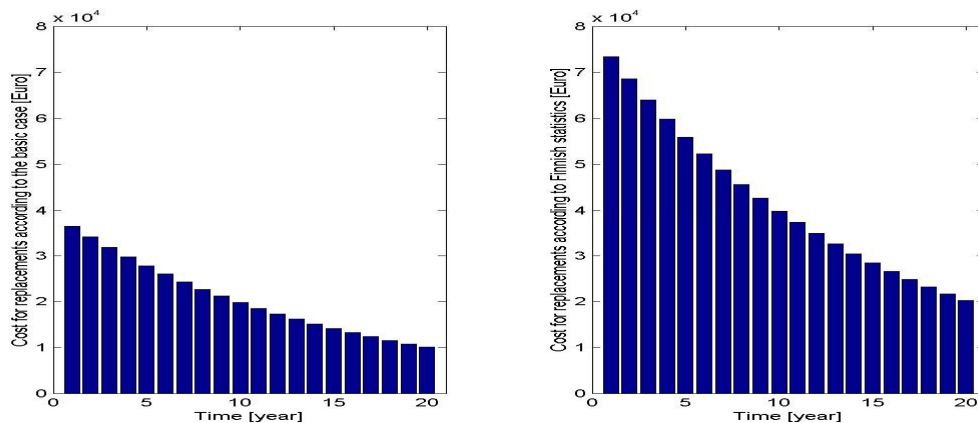


Figure 4.9 Present value of costs for replacements of major components with replacements every year at Olsvenne2 with data from the basic case and statistics from Finland respectively.

4.6.4 Different discount rates

Without CMS

The discount rate was changed to see how a change in discount affects the results. The total sum of present value of *LCC* has been calculated with the discount rates of 0 %, 7 % and 10 %.

For present value analysis with the effect of different discount rates on Olsvenne2 and Kentish Flats see Table 4.5 where replacements of major components have been made according to the basic case and Kentish Flats respectively.

Table 4.5 Present value analysis with the effect of different discount rates on Olsvenne2 and Kentish Flats.

Discount rate %	Total sum of the present value of <i>LCC</i> [Euro]	
	Olsvenne2	Kentish Flats
0	4 430 000	5 033 100
7	3 719 100	4 250 400
10	3 567 800	4 071 900

For present value analysis with the effect of different discount rates on Olsvenne2 and Kentish Flats see Table 4.6 where replacements of major components have been made according to Finnish statistics.

Table 4.6 Present value analysis with the effect of different discount rates on Olsvenne2 and Kentish Flats with replacements according to Finnish statistics.

Discount rate %	Total sum of the present value of <i>LCC</i> [Euro]	
	Olsvenne2	Kentish Flats
0	5 219 600	6 302 700
7	4 137 300	4 922 900
10	3 903 900	4 612 300

The total cost is for a single turbine even for Kentish Flats.

With CMS, strategy 4 to 6 for Kentish Flats

For strategy 4 to 6 the discount rate has then been changed to 0% and 10 % respectively, and the difference in the total sum of the present value of *LCC* has been calculated. For present value analysis with the effect of different discount rates at Kentish Flats see Table 4.7 where the difference in the total sum of the present value of *LCC* is shown for strategy 4,5,6. The cost for 30 CMS is 600 000 Euro.

Table 4.7 Present value analysis with the effect of different discount rates for strategy 4, 5, 6.

Discount rate %	Difference in Total sum of the present value of <i>LCC</i> [Euro]		
	S4	S5	S6
0	1 836 090	430 000	1 320 000
7	1 014 900	227 770	699 200
10	839 400	183 040	561 900

For example TPV(*LCC*) for strategy 5 does not on its own cover the cost for 30 CMS with any discount rate. The strategies can be combined so that the cost for 30 CMS is covered. In strategy 4 unscheduled maintenance becomes preventive and the man days are reduced by 5 %. In strategy 5 the man days within the cost for replacements of major components are reduced so that the components are replaced two at a time instead of one at a time. In strategy 6 the availability is increased by 0,5 % into 98 % and this affects the cost for production loss.

4.7 Conclusions

If only the preventive maintenance is affected, when a CMS is implemented, the preventive maintenance has to decrease by 23 % to make a CMS profitable for the single turbine onshore, the corresponding result for the average turbine offshore was 4,5%. If the corrective maintenance also is affected the preventive- and corrective maintenance do not have to decrease by more than 3,5 % for the turbine onshore, the corresponding result for the average turbine offshore was 2,5 %.

When costs for an entire farm are observed 47 % of the unscheduled maintenance has to become preventive maintenance to make a profit on CMS. It is difficult to make a profit on CMS only through replacing components two at a time instead of one at a time but it gives a significant contribution to the cost for CMS. If several components are replaced at a time the contribution cannot be enough to cover the cost for CMS. It is enough to increase the availability by 0,43 % to cover the cost for CMS through a decrease in the cost for production loss.

There are many ways to cover the cost for CMS especially at a farm offshore if both the preventive- and corrective maintenance is affected. At least for the onshore turbine the corrective maintenance must be decreased to motivate CMS.

5 Closure

5.1 Conclusions

Is CMS a good solution for the wind power user? Maybe not in the separate wind turbine but in larger farms with the same type of turbine it could be interesting. The cost of changing an entire gearbox is almost the same whether it has gone through a total breakdown or if it is changed at the right time [1]. And at least with Vestas CMS system the wind power user does sometimes not have access to the data. The prices must go down and data must be available if this should be a durable solution.

Whether RCM in combination with CMS has a future in wind power applications in Sweden is still to be seen. It has already been used by SKF with long experience in Scotland where both SKF's own CMS system WindCon and other systems are used. Maybe it could be a solution for offshore farms with a large amount of similar types of turbines like Lillgrund, a farm that is to be built between Denmark and Sweden close to the Öresund bridge.

To get an understanding if whether CMS is profitable or not a LCC (Life Cycle Cost) analysis has been made. The total cost, *LCC*, is compared for different alternative maintenance strategies.

The first three strategies gave the results for the single turbine that if only the preventive maintenance is affected the preventive maintenance would have to decrease with 23 %, the same result for the farm was 4,5 %. If even the corrective maintenance would be affected the preventive- and corrective maintenance together would not have to decrease by more than 3,5 % for the single turbine and 2,5 % for the farm. Decreased corrective maintenance is needed to motivate CMS, at least for the turbine onshore.

When an entire farm was observed the conclusions were that a change from scheduled to unscheduled maintenance with 47 % would be enough to make CMS profitable. To replace components two at a time instead of one at a time would not be enough to make CMS profitable but it would give a significant contribution. The availability would not have to be increased with more than 0,43 % to get a reduction in cost for production loss that would cover the cost for CMS. There are many ways to cover the cost for CMS, especially for the wind farm offshore where maintenance could be planned in a better way with CMS.

5.2 Future work

The LCC analysis performed within this study could be refined. Costs for different maintenance tasks could be much more detailed but this demands a lot of work.

When it comes to RCM combined with CMS in wind turbines there is a lot of work that can be done. Much has been done but not in Sweden. But there is much experience that could be found in for example Scotland and USA.

To follow the development of wind farms offshore, for example Lillgrund, and see the possibilities and benefits of RCM and CMS in a farm with the same type of turbine would be a further step. To be able to plan maintenance with RCM a system that collects data is needed. CMS here comes in as a formidable tool.

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- [3] Visit to Smöla Wind Farm and interview with Arild Soleim, Maintenance Manager Statkraft A/S.
- [4] Interview with Inge Aasheim on SKF Business Development – Wind Energy Aftermarket.
- [5] Interview with Fredrik Larsson, Managing Director on SKF Condition monitoring Center.
- [6] Interview with Per-Erik Larsson, Manager, Production Development and Technical Support on SKF Condition Monitoring Center.
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