Condition based control

Take the load off damaged components

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Summary

Offshore wind farms are expensive to maintain and it is difficult to achieve a similar availability to onshore farms. This report examines the possible benefit of condition based control, where the controller is adapted to modify the loading of parts depending on their condition. This benefit is only examined in terms of annual electricity production. Other, secondary benefits may be possible, but are not considered.

Literature indicates that the most relevant parts are the drive train, the blades and the pitch systems. Literature does not give a clear relation between loading and remaining life time of the components, so it is assumed that the remaining life time is inversely related to the loading of the parts.

An Operations & Maintenance (O&M) case study into the maximum possible benefit of the condition based maintenance (CBM) and condition based control shows that an Annual Energy Production (AEP) increase of up to 2% can be achieved. For the considered reference wind farm (consisting of 120 3MW wind turbines), this boils down to 72 M€ over the lifetime of the farm. However, this figure represents an upper limit on the achievable benefit as it is based on an ideal scenario. More specifically, it is computed by assuming that, (a), CBM is applied to all turbine components, and (b), that the condition signal is always received enough time in advance of the actual failure to allow for performing the O&M planning and waiting activities before the actual failure occurs. The calculation of a more accurate estimate of the achievable benefit requires more detailed data on the failure prediction capabilities of the condition monitoring systems, which was not available in this study. However, if for example CBM is applied to only 50% of the cases, and if the assumed percentage of the logistics/waiting time that the turbine remains in operation is reduced from 100% to 30%, the lifetime revenue increase would drop down to the more realistic value of 10.8 M€.

With respect to condition based control, two methods have been investigated: power down-regulation and a novel pitch reduction control. Both methods deliver fatigue load reductions at the expense of some power loss, but are complementary as they target different components. In terms of economic benefits, significant revenue improvements are estimated for condition based control, ranging from 1.5-1.7 M€ (for the gearbox and the yaw mechanism) to 2.7 M€ (for the pitch system). These benefits come on top of the benefit from CBM, mentioned above.

1. Introduction

Offshore wind farms are not as easy to maintain as onshore ones. There are multiple factors to blame: it takes longer to get to the wind turbine, higher average wind speeds reduce the opportunity for certain repairs, high waves limit how often wind turbine can be accessed by boat and crews and vessels are also in limited supply. Furthermore, vessels and crews are significantly more expensive in case of an offshore wind farm.

Despite these challenges, offshore wind farm availability has been improving steadily and significantly over the last few years (The Crown Estate, 2016) and currently varies between 90% and 95% for the UK offshore wind farms (SPARTA, (System Performance, Avialability and Reliability Trend Analysis), 2017). Any method that can further increase the availability of the wind farm in a cost effective way is of interest.

This report investigates using the controller to reduce the downtime (and thus increase availability) by reducing loads on parts where a condition monitoring system indicates a fault may be developing. This approach will be referred to as 'Condition based control'. Because only the control of the wind turbine is adjusted, hardly any additional operation cost is involved in increasing availability, the trade-off is between gained production and the measures required to achieve lower loading.

The rest of this chapter explains the concept of condition based control, explores which parts are relevant and examines condition monitoring systems and their operations and maintenance context.

Chapter 2 examines an O&M case study to see what the potential benefits are while Chapter 3 examines the effect of adapting the wind turbine controller on the loads and whether it is possible to create an effective condition based control system. Finally, Chapter 4 draws the main conclusions and recommends further research.

1.1 What is condition based control?

The idea behind condition based control (CBC) is that some curtailment of the wind turbine is used to reduce the loads on a system that is about the fail. The idea is that by reducing the loads, the failure of the system is delayed and the wind turbine will be operational for a longer time and will produce more energy over its lifetime than without the load reduction.

1.1.1 Costs versus savings

To be able to judge the value of CBC, we examine three scenarios, that are illustrated in figure 1:

Scenario 1: repair on failure
In this scenario, the wind farm operator only able detects what failure occurred, after the fact. Up to the moment of the failure, the wind turbine runs at full power. Only after the moment of failure, a repair is planned and executed. After the repair, the turbine starts running at full power again (weather permitting).

Scenario 2: condition based maintenance
The presence of a condition monitoring system allows the operator to start planning a repair before the failure actually occurs. Otherwise no action is taken and the turbine remains running at full power until failure occurs. Down time can be reduced by the time between detection and failure, power production increases accordingly.

Scenario 3: condition based control
After detection, the turbine is instructed to use reduced operation to delay the failure. Ideally, failure is delayed up until the point of repair. That means that power is lost between the point of detection and the point of (undelayed) failure, but the wind turbine can still generate power after that point, because the failure of the part is delayed. Ideally, this reduced production could be maintained up until the point of repair.

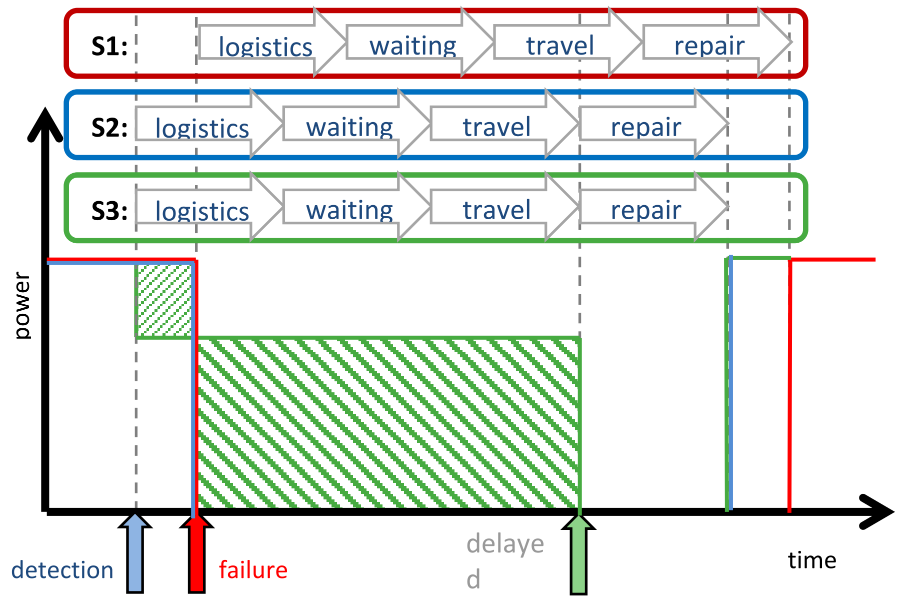

Figure 1 Three scenarios are examined that lead to different amounts of production loss

Figure 1 shows that for CBC to be worthwhile, the power produced after the expected point of failure, must exceed the loss in power production up to the point of failure (the hatched areas respectively to the right and the left of the normal failure point).

For example, if a 10% reduction in power results in in 10% longer time-to-failure, there is no net benefit. However, if a 10% reduction in power can achieve a 20% extension in the time-to-failure, there is a benefit to employing condition based control. Obviously, the higher the ratio of the time-to-failure extension to the power reduction, the better.

The figure also indicates that if the detection is very early, i.e. if there is long time between detection and failure) and maintenance is planned immediately, (scenario S2), then the difference between scenario s2 and s3 becomes quite small.

1.1.2 Assumptions

There are some assumptions that underlie the concept of Condition Based Control and these are:
- Condition monitoring systems can reliably detect failures sufficiently early, such that a reduction in loads can meaningfully extend the time-until-failure.
- Reducing the load on the affected parts delays the occurrence of a failure.
- The time-until-failure can be predicted with reasonable accuracy

1.1.3 Possible additional benefits

Apart from reducing the power loss due to downtime, there may be other cost benefits to being able to delay failure.

Preventing additional damage
It may be possible to use the controller to avoid maintenance costs, by reducing the loads such that complete failure is avoided, rather than maximum energy is produced.

Combination of repairs
It may also be possible to run on a reduced level for a little longer and combine repairs on several wind turbines or with preventative maintenance actions. This could lead to additional cost savings. However:
- The benefits depend on the components, whether or not they can be combined with other activities and the timing of their failures. To quantify this, more detailed information on vessel and crew capabilities is needed and more detailed operational planning would have to be modelled.
- To evaluate the final results, a significantly higher number of simulations would have to performed. Therefore, this secondary saving, although possibly significant, is not examined.
- It is not clear to what extent, the same strategy could be used for scenarios 1 and 2.

Because of these reasons, the combination of repairs is not examined as a possible additional cost saving.

Maximising the value of the produced energy
Finally, condition based control could provide further benefits if the value of the energy is included. This would be particularly relevant in grids without a feed-in-tariff and variable pricing. In the default case, energy is produced regardless of the price of electricity. If condition based control is employed, it may be possible to consume the remaining life time of the part and produce energy when the price of electricity is particularly high.

The benefit of this option is hard to quantify. Furthermore, it only applies to wind turbines operating without a feed-in-tariff.

1.2 Components and failure rates

To create effective strategies, condition based control should focus on those components that contribute most to the total downtime of the wind turbine. This is important, because not all components are equally likely to fail, or require an equal amount of time to repair. As an added complexity, different wind turbine models will have different components that fail.

The focus is on failures of the mechanical parts of the wind turbine, rather than failures of components of the electrical systems. This is because the condition of electrical components is difficult to observe and the way to control is not obvious: some components fail because they are subject to vibrations, others fail because of temperature variations or other causes of degradation. However, if a condition monitoring system is available and failure could be delayed by changing the controller in some way, then condition based control could be a viable option.

The purpose of this section is to identify the components of wind turbine systems which are subjected to the most failures and subsequently the most downtime due to failures. The section gives an overview of literature related to stoppages, downtime and failures of wind turbines, both installed onshore and offshore. Based on the data available, systems and subsystems can be identified which may benefit from implementation of load reductions based on damage signals from condition monitoring.

While the focus of this study is on the offshore case, for determination of components that would benefit most from condition monitoring, the onshore case is considered as well. It is indicated by Faulstich (Faulstich, Hahn, & Tavner, 2011) that the offshore wind turbine industry has been derived from onshore technology. For this reason, similar faults can be expected. However, for the offshore case, faults and failures are likely to result in increased downtime due to limited accessibility, weather requirements, as well as the need for specialised equipment for repairs.

1.2.1 Availability of wind farms

According to Hahn (cited in (Faustich, Hahn, Lyding, & Tavner, 2009)) and Faulstich (Faulstich, Hahn, & Tavner, 2011), onshore wind turbines in Europe achieve an availability in the range of 95 to 99 percent. For offshore systems, the availability is significantly reduced. Faulstich (Faulstich, Hahn, & Tavner, 2011; Faustich, Hahn, Lyding, & Tavner, 2009) provides data for the availability of various offshore wind farms as presented in Figure 2.

Stoppages reducing availability are attributed to faults, poor conditions, as well as preventative and corrective maintenance. The latter is can be attributed to failures experienced in various turbine systems, sub-systems and components. It is suggested by Faulstich (Faulstich, Hahn, & Tavner, 2011) that failures are likely to be more significant in the offshore case, compared to the onshore case. This is credited to longer waiting, travel and work times for offshore in turbines. In attrition to this, it is suggested that with distances of wind farms from shore increasing to over 50 km, the availability may decline from the presented values.

Furthermore, Faulstich (Faustich, Hahn, Lyding, & Tavner, 2009) shows that there is the highest failure rated in wind turbines in the first production and operating year. That is, wind turbines manufactured after the first year of production have increased reliability due to experience gained from previously manufactured turbines.

These results give evidence to support the claim that offshore wind farms may benefit from the proposed predictive operations and maintenance strategy. This is particularly true as the size of offshore wind turbines increases, and due to the associated relatively lower reliability of larger systems (Crabtree, Zappalá, & Tavner, 2014). Thus, condition monitoring and load reductions may show the greatest benefit for large turbines in reducing downtime and maintenance costs, particularly in the early life of the systems.

The sections which follow are dedicated to determining which turbine systems and components contribute most to failures, stoppages and reduced availability in wind farms. Whilst the focus of this study is on offshore wind turbines, the data available is limited. Multiple studies and large datasets are available for onshore wind energy which can give indications as to likely components, systems and subsystems which may be responsible for the lowered availability in the offshore case. It is these systems, subsystems and components in which the proposed predictive maintenance strategy may contribute most in increasing in wind farm availability and reducing cost of energy.

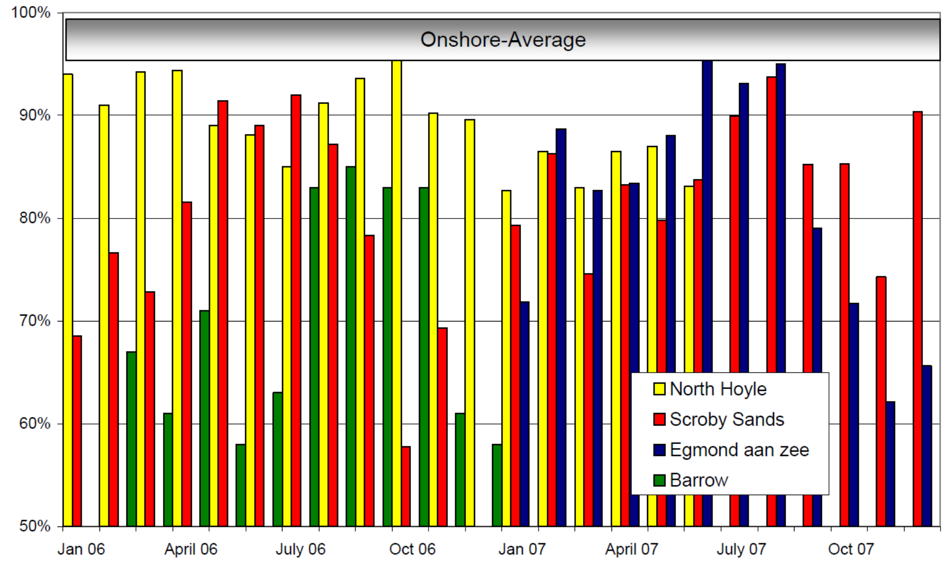

Figure 2 Comparison between onshore and offshore availability of selected wind farms (Faustich, Hahn, Lyding, & Tavner, 2009)

1.2.2 Onshore wind farms

Many studies have been conducted concerned with the reliability of onshore wind turbines. Determining the sub assembly failure rate, and the associated downtime per failure gives an indication of sub-systems which can benefit from condition monitoring. Data presented in such studies is given in this section.

Crabtree (Crabtree, Zappalá, & Tavner, 2014) presents the failure rates and downtime from three surveys ((Feng & Tavner, Introduction to wind turbines and their reliability and availability, 2010; Tavner, Spinato, van Bussel, & Koutoulakos, 2008) cited in (Sheng & Yang, Wind turbine Drivetrain Condition Monitoring - An Overview, 2013), (Ribrant & Bertling, 2007) cited in (Wilkinson, Harman, & Hendriks, 2011)) of European onshore wind turbines collected over 13 years with a cumulative data set of 24300 turbine years (see Figure 3).

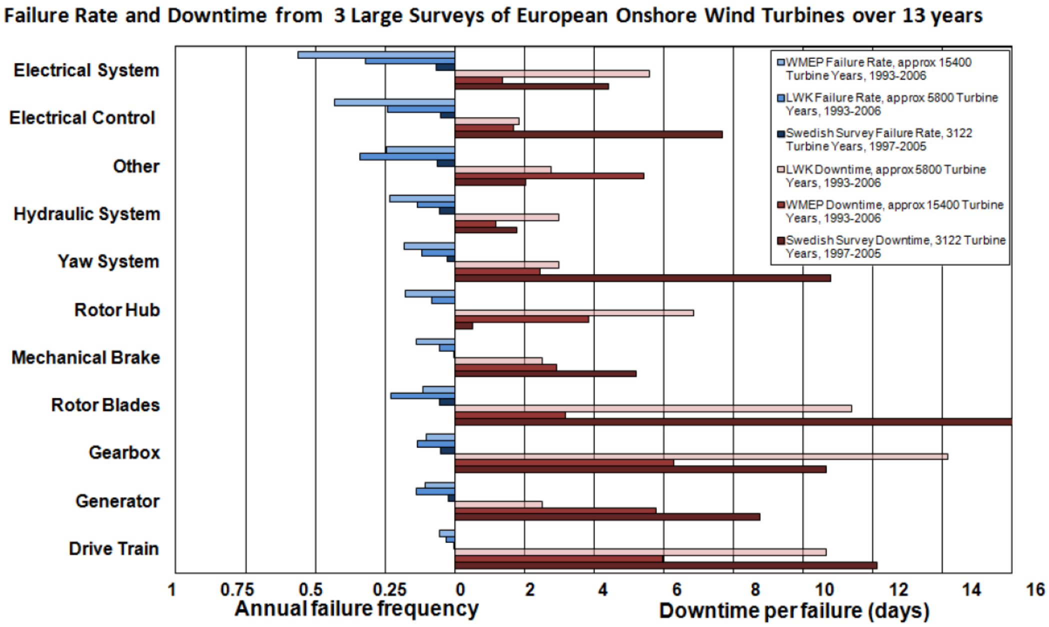

Figure 3 Wind Turbine failure rate and downtime for various components (Crabtree, Zappalá, & Tavner, 2014)

As part of the EU FP7 Reliawind project, Wilkinson (Wilkinson, Harman, & Hendriks, 2011) presented the reliability of existing wind turbines from several operational wind farms. This study utilised data constructed information provided from 10 minute SCADA as well as service records, work orders and alarm logs to give an indication of the subsystem reliability. The database, published in 2010, contains approximately 350 specification of wind turbines from sites with more than 15 turbines with output greater than 850 kW. Figure 4 and Figure 5 give the data presented by Wilkinson (Wilkinson, Harman, & Hendriks, 2011) showing the normalised failure rate for subsystems and assemblies as well as the hours lost per turbine per year to faults.

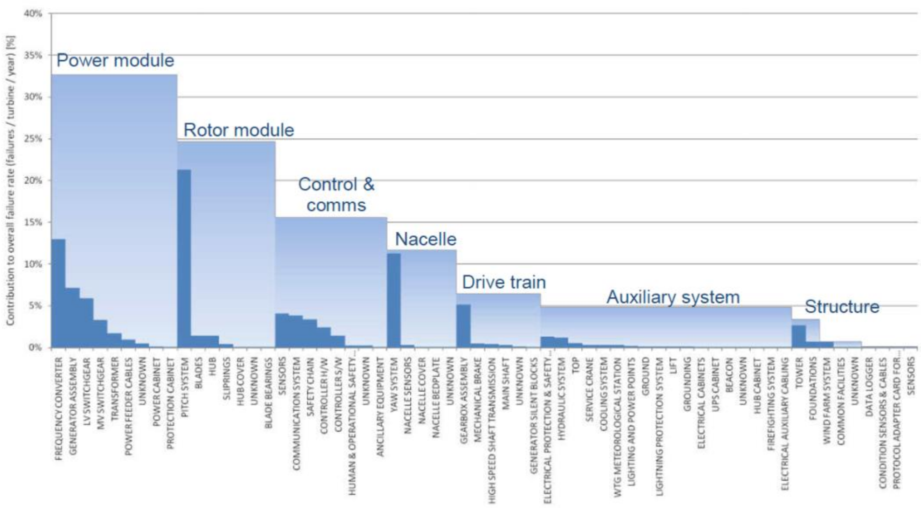

Figure 4 Normalised failure rate of sub systems and assemblies (Wilkinson, Harman, & Hendriks, 2011)

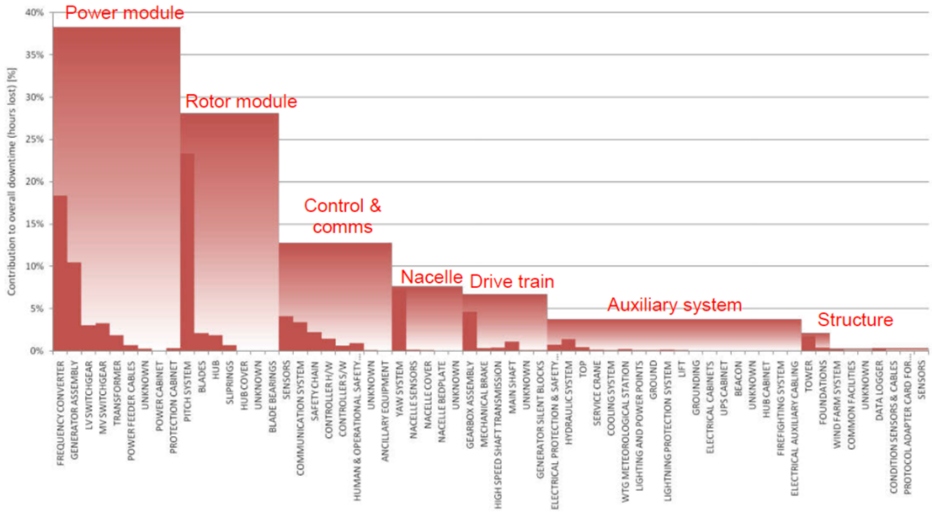

Figure 5 Normalised hours lost per turbine per year due to faults (Wilkinson, Harman, & Hendriks, 2011)

1.2.3 Offshore wind farms

Data is limited in regards to offshore wind turbine failures and downtime. The most comprehensive data set available to the authors knowledge is taken from the Egmond aan Zee offshore wind farm operations reports from 2007 through 2009 (Nordzee Wind CV, 2008; NoordzeeWind CV, 2009; NoordzeeWind CV, 2010). The wind farm is made up of 36 Vestas V90 3 MW wind turbines with a cumulative installed capacity of 108 MW. The available Operations Reports categorize stoppage causes and summarize the number of stoppages for each category as well as the cumulative downtime. Whilst the data available allows an indication of components which may benefit from condition monitoring systems, it is seen that stoppages noted in this data set differ from a failure, which are given in other literature sources and also presented in this study as a measure of reliability. The data available represents 108 years for the given Vestas turbine. The data was combined and averaged to give an indication of the expected yearly number of stoppages for each category, as well as the associated average downtime per stoppage event. This data is presented in Figure 6.

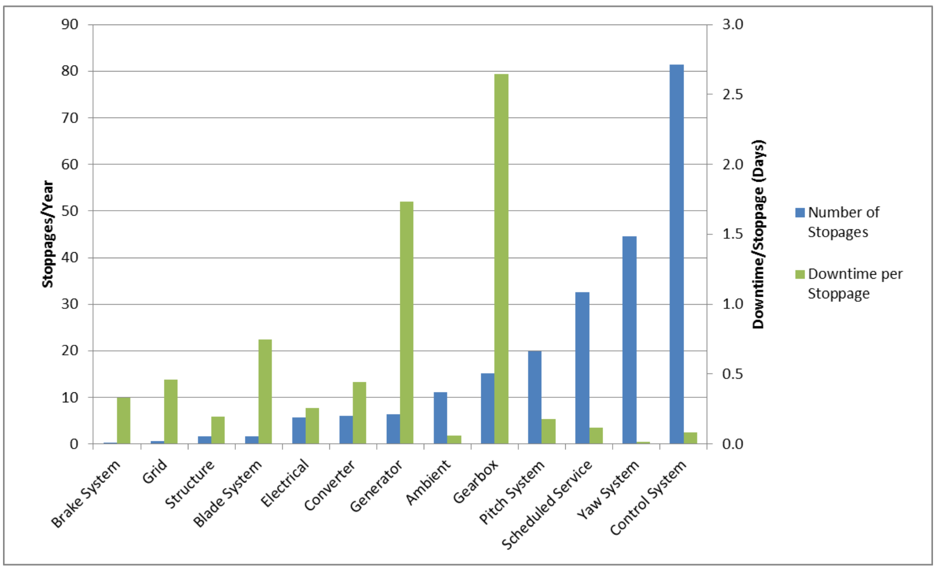

Figure 6 Average yearly stoppages and downtime Egmond aan Zee 2007-2009 (Nordzee Wind CV, 2008; NoordzeeWind CV, 2009; NoordzeeWind CV, 2010)

Based on the results of Figure 6 the average yearly cumulative downtime for a wind turbine for each category has been derived as seen in Figure 7. Also shown in the figure is the generating capacity lost due to failures and other anomalies leading to downtime.

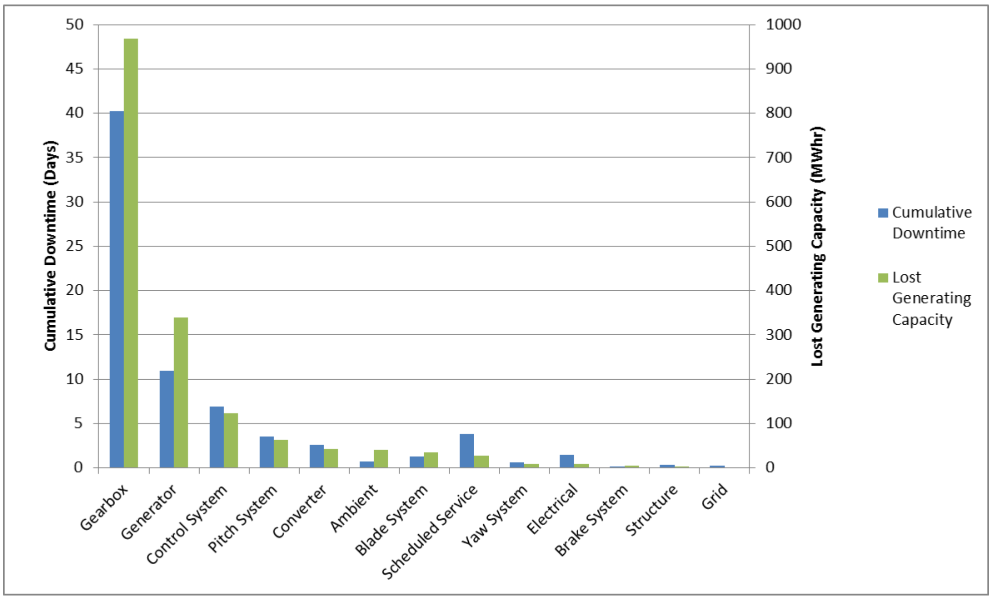

Figure 7 Average yearly downtime and lost generating capacity Egmond aan Zee 2007–2009 (Nordzee Wind CV, 2008; NoordzeeWind CV, 2009; NoordzeeWind CV, 2010)

As noted, sources of data for failure of offshore wind turbine components are limited. The ECN developed Operations & Maintenance Tool also contains default values for the yearly likelihood of failure of offshore wind turbine components as well as the probability that the failure falls into a given maintenance categories indicating the average downtime for each failure event. These values have been derived from both historical literature data that is available for onshore and offshore turbines, as well as through interactions with customers and clients who have provided feedback on their systems. A default data set is presented in Figure 8 which may give further details on components of which condition monitoring could benefit.

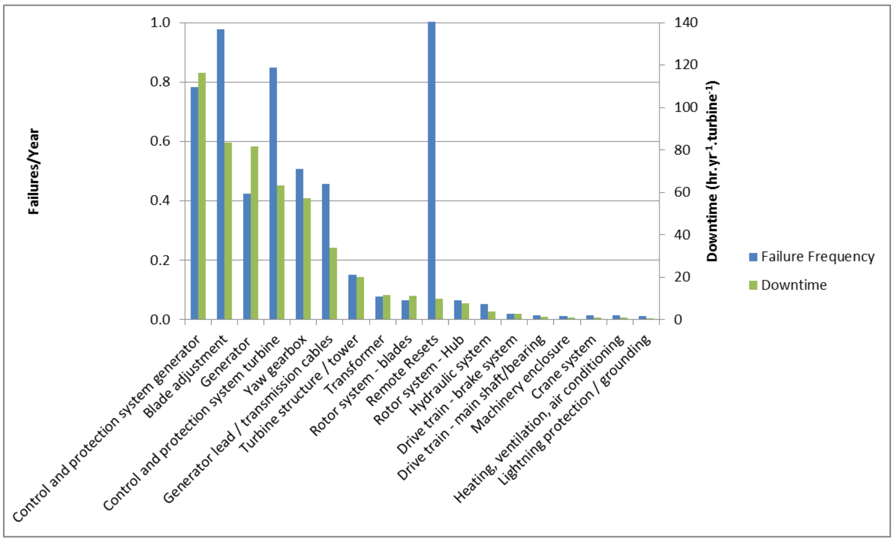

Figure 8 ECN Operations & Maintenance tool default downtime and failure frequency values

1.2.4 Systems and subsystems for condition monitoring

Condition monitoring systems are implemented with the purpose of detecting system faults which may lead to adjustments in operation or maintenance strategies to reduce cost of energy. Wisznia (Wisznia, 2013) gives three criteria which must be met for the detection of faults and a successful condition monitoring system. These are summarised as follows:

1. Reliable detection ability
2. Early detection possibility
3. Potential reduction in maintenance costs

Based on the data collected from Figure 3 through Figure 8, it can be determined which components and subsystems contribute to the greatest downtime in wind turbines. At this stage, identifying trends in the data set is required to narrow the scope of this study. In determining the systems which may benefit most from condition monitoring, the citeria mentioned above must be taken into account.

In general, the data from the three surveys conducted in Figure 3 varies greatly from survey to survey in both the annual failure frequency and the downtime per failure. For the Swedish survey, the annual failure frequency is lower than the other surveys. The downtime per failure is also higher than the other two surveys in 6 of the 11 surveys conducted. This may be attributed to the dataset not inclusive of the four years 1993 through 1996, however the full reasons for this are not clear. The LK and WMEP surveys contain data for the same year range, yet the data sets vary greatly. It is notable that many of the components for all surveys contain low annual failure rates, (< 0.25), suggesting mature technology levels.

It should be noted that some studies indicate condition monitoring systems are prohibitive due to their high cost and inability to prevent multiple failures. Despite this, the downtime per failure may give a more indicative picture as to the subsystems which may benefit from condition monitoring. The use of the ECN Operations & Maintenance tool in Chapter 4 can further investigate the monitoring of which subsystems gives the greatest benefit.

The electrical system and control subsystems appear to have lower average downtime than other mechanical components presented. This suggests that mechanical components are more likely to contribute to greater downtime. In the context of this study, this result is positive as electrical components are less likely to benefit from load reductions when compared to mechanical systems. In general, it is determined from Figure 3 (database 1) that the components listed in Table 1 are most likely to contribute to high system downtimes and as such preventative methods for failure should be implemented.

Figure 4 and Figure 5 give normalised data for the contribution of various components and subsystems to the total failure rate as well as the overall downtime hours. The most notable aspect of these results is the subsystems with the highest failure rate are those which contribute to the highest cumulative downtime. These subsystems are identified in Table 1 (database 2, ignoring communications and control):

When taking into account the data from the Egmond aan Zee wind farm, Figure 6 shows that the gearbox, generator and blade system contribute the highest downtime per stoppage. However, they have low relative failure rates (mature technology). The derived cumulative downtime from

Figure 7 suggests for the OWEZ wind farm that the subsystems contributing to highest cumulative downtime are as shown in Table 1.

Database 1	Database 2	Egmond aan Zee	Further Analysis
Yaw System	Frequency Convertor	Gearbox	**Gearbox**
Blade System	Generator	Generator	**Generator**
Gear Box	Pitch System	Blade System	**Blade and Tower System**
Generator	Yaw System	Pitch System	**Pitch and Yaw Systems**
Drive Train	Gearbox	Frequency Convertor	
	Tower	Yaw System	

Table 1 Systems with highest downtime per stoppage from various sources

Based on the data presented, subsystems which show likely benefit from the combination of condition monitoring and load management are taken for analysis which is conducted in the following chapter. Current condition monitoring strategies for these systems are presented from the literature as well as any data available which gives an indication as to how they may benefit from the proposed O&M strategy.

1.3 Condition monitoring systems

This section outlines the monitoring systems that are available in wind turbines as well as current condition monitoring strategies already utilised in wind turbine systems based on information provided in the literature. In addition to this, this chapter also identifies relevant research which has been conducted in regards to condition monitoring on these systems. The chapter only considers 'online' monitoring strategies, and neglects 'offline' ones which may include visual inspections, taking oil samples, etc.

1.3.1 Monitoring systems

According to Crabtree (Crabtree, Zappalá, & Tavner, Survey of commercially available condition monitoring systems for wind turbines, 2014), monitoring systems on wind turbines are broken down into four categories:

1. Supervisory Control and Data Acquisition (SCADA) (<0.002 Hz, Continuous)
2. Structural health monitoring (<5 Hz, On demand)
3. Condition monitoring (<50 Hz, Continuous)
4. Diagnosis (>10 kHz, On Demand)

SCADA monitoring systems were originally utilised for measuring the power output of wind turbines, however their functionality has been extended to the monitoring of other signals. According to Yang (Yang, Tavner, Crabtree, Feng, & Qiu, 2012) and Crabtree (Crabtree, Zappalá, & Tavner, Survey of commercially available condition monitoring systems for wind turbines, 2014), the SCADA system is responsible for monitoring systems and alarms usually at 10 minute intervals, ensuring the wind turbine is conforming to its power curve as well as running safely and efficiently. According to Yang, the SCADA system will usually measure the following signals:

1. Active power output and standard deviation
2. Reactive power
3. Power factor
4. Generator current and voltages
5. Anemometer measured wind speed and standard deviation
6. Turbine generator and shaft speed
7. Gearbox bearing and lubrication oil temperature
8. Generator winding and bearing temperatures
9. Average nacelle temperature

It is suggested that the limiting factor in utilising the SCADA measurements for fault analysis is the low (10 minute) sampling rate. Whilst SCADA systems are able to provide fault signals, this low sampling rate ensures the systems often provide false alarms or alarms which are too frequent for proper analysis. There is however, work being conducted on using SCADA data for condition monitoring as the systems are available at no extra cost. Research has been conducted to utilise such systems for condition monitoring through increasing the sampling frequency (EU FP6 CONMOW project (Wiggelinkhuizen, et al., 2008)) or the development of signal algorithms for false alarms (EU FP7 Reliawind project (Wilkinson, Harman, & Hendriks, 2011)), however, as yet no such method has proved reliable for successful condition monitoring. Wiggelinkhuizen (Wiggelinkhuizen, et al., 2008) concluded that no evidence was found that monitoring SCADA measurements provided a method for determining early failures or remaining lifetime. Yang also concluded that these systems were unable to carry out diagnosis or prognosis (Yang, Tavner, Crabtree, Feng, & Qiu, 2012). This provides a basis for the requirement of a dedicated condition monitoring system.

Structural health monitoring systems are used to measure the structural integrity of the wind turbine tower, foundations and blades. It was identified in Chapter 2 that the wind turbine tower structure, foundations and blades are not large contributors to downtime. Despite this, structural monitoring is of importance in the current study for reasons to be provided in the following section (3.2).

Condition monitoring techniques have been utilised for many years in many industrial processes. The commercial application to wind turbines has been accelerated over the past 20 years due to the global growth of the industry and the indicated potential of condition monitoring systems in reducing the cost of energy (Wiggelinkhuizen, et al., 2008; Sheng & Yang, Wind turbine Drivetrain Condition Monitoring - An Overview, 2013). Wiggelinkhuizen (Wiggelinkhuizen, et al., 2008) estimates that a successful condition monitoring system can reduce cost of energy in the range of 25% – 30%. There are number of drivers for the implementation of condition monitoring systems. Yang (Yang, Tavner, Crabtree, Feng, & Qiu, 2012) identifies the five main drivers as sites, diversity, size, control and cost. That is:

- The erection of wind turbines in remote sites and locations (offshore)
- The diversity of wind turbine designs (geared, direct drive, semi-direct drive)
- Lower manufacturing and installation costs leading to the size of turbines increasing. Yang suggests that although the reliability of a wind turbine should be independent of speed, studies have shown that large turbines experience more failures than smaller ones.
- The use of more intelligent control in modern wind turbines including variable speed systems, intelligent blade pitch , etc.

- Countering the cost of installation and connection costs of offshore wind energy

A condition monitoring system is implemented in a wind turbine in addition to the SCADA system. The system is used to detect faults by measuring data from various sensors and systems and transferring the data to a central node for processing. In general, condition monitoring is broken down into three steps (Wisznia, 2013; Wiggelinkhuizen, et al., 2008):

1. **Detecting symptoms**: Symptoms are detected by monitoring signals and noting ones which fall outside of a certain range. In some instances, signals must fall outside this range on multiple occasions to be considered a fault.
2. **Diagnosing fault**: Determining the cause and location of the symptom observed from the monitoring of signals.
3. **Forecasting**: This involves determining the remaining longevity of the component or system based on the diagnosed fault.

Authors (Yang, Tavner, Crabtree, Feng, & Qiu, 2012; Grey & Watson, 2010) often cite the challenge of ensuring condition monitoring systems achieve value for money. Yang (Yang, Tavner, Crabtree, Feng, & Qiu, 2012) cites the SKF WindCon condition monitoring system with cost of 14 k£/unit for software, transducers, cabling and installation, suggesting the installation of a dedicated system on individual turbines is a significant investment. Justification of the cost for larger rotating machinery (gas/steam turbines) which may be as large as 500 MW is easier than individual ±1-5 MW units. Despite this, high cost of repairs, offshore attendance and downtime ensure there should be benefit in wind turbine condition monitoring systems.

The fault diagnosis system is initiated on demand, either automatically or by an engineer when a symptom is detected. In order to diagnose the fault, data is recorded at a high sampling frequency for a limited time until fault can be identified.

1.3.2 Monitoring and load management in the overall O&M strategy

Large distances to shore, unfavourable wind condition and the need for specialised crews and equipment ensure there is limited access to offshore wind farms. The effect of limited access to the wind farm is that maintenance cannot be performed immediately if a fault or failure is detected. It is proposed (Griffith D. T., Yoder, Resor, White, & Paquette, 2014; Griffith D. T., Yoder, Resor, White, & Paquette, 2012) that O&M costs of offshore wind turbines can be reduced with the use of a condition based maintenance strategy with smart load management. Literature sources suggest condition monitoring and structural health monitoring are able to provide benefits in improving and optimising operational and maintenance procedures. However, in most cases of detecting an imminent failure through a monitoring system, no changes to the operating conditions (damage mitigating control) of a wind turbine are proposed.

Griffith (Griffith D. T., Yoder, Resor, White, & Paquette, 2014; Griffith D. T., Yoder, Resor, White, & Paquette, 2012) indicates a number of benefits of derating of a wind turbine in order to reduce loads and fatigue damage leading to increased life of components and systems:

- If maintenance cannot be performed at time failure is detected, down-regulation of the turbine can be induced such that revenue is still generated without further significant damage being inflicted.
- Potential reduction of repair costs through lowering failure class or severity.
- Possibility of servicing multiple turbines during single wind farm visit.

- Postponing corrective maintenance to scheduled preventative maintenance period.

Few examples in the literature have been found which outline the benefit of load management in addition to wind turbine monitoring. Many studies are concerned with active control methods for reducing loads on the structural elements of wind turbines (tower/blades) (Wingerden, et al., 2008; Houtzager, van Wingerden, & Verhaegen, 2013; Bergami & Poulsen, 2014; Bossanyi, 2003; Lackner & van Kuik, 2010; Griffith D. T., Yoder, Resor, White, & Paquette, 2014; Griffith D. T., Yoder, Resor, White, & Paquette, 2012; Ciang, Lee, & Bang, 2008). Focus is on the blades of the turbine as these are key components. Flemming (cited in (Ciang, Lee, & Bang, 2008)) states that the cost of the blades can account for 15%-20% of the total turbine cost as well as been the most costly type of damage to repair with the greatest turbine downtime. Additionally Rosenbloom (cited in (Ciang, Lee, & Bang, 2008)) indicates that failures of blades leading to rotating mass imbalances can lead to the propagation of much more serious damage to the turbine components including the tower itself. The many studies focusing on active control of blades indicate its necessity in order to not only minimise the weight and cost of blades, but more so to achieve (fatigue) load reductions which can lead to damage and failure of various components.

Griffith (Griffith D. T., Yoder, Resor, White, & Paquette, 2014; Griffith D. T., Yoder, Resor, White, & Paquette, 2012) conducted a modelling study to determine the possibility for damage mitigating control on a 5 MW offshore wind turbine when a trailing edge disband failure occurs on a blade. The main finding was that decreasing the turbine power production by as little as 5% could result in a reduction on the equivalent loading by 10% and thus the blade fatigue life could be extended by a factor of 3. This result gives evidence to suggest derating a turbine due to damage signals can benefit the O&M strategy and minimise downtime, particularly if this result can be extrapolated to high failure frequency/downtime components (section 2.4) on a wind turbine. To the authors knowledge, no studies exist which investigate the effect of active load management on increased lifetime for non-structural elements (gearbox, generator, yaw systems) of wind turbines. Despite this, Lackner (Lackner & van Kuik, 2010) and Adams (Adams, White, Rumsey, & Farrar, 2011) indicate that load reductions on the rotor blades can lead to reduced loads in other locations including the drivetrain due to the interaction between components. Furthermore, Jalalahmadi and Steen (Jalalahmadi & Steen, 2014) state that derating of a turbine has the ability to reduce torque and load on turbine components, which may extend their operating life. This gives evidence to suggest active load control could be beneficial to increasing lifetime in other turbine components, however more evidence needs to be sought to quantify this.

It can be concluded that the combination of smart monitoring systems in wind turbines, combined with damage mitigating control allows further optimisation of the predictive O&M strategy and reductions in the overall cost of energy through the increase in component and system lifetime, reduction in unplanned maintenance events and logistical lead time. Determining quantitatively the full benefits of load reductions in terms of increases in component and system lifetime are required for understanding the full benefit of including this methodology in the overall O&M strategy.

1.3.3 Systems and subsystems

Many commercially available Condition Monitoring systems, mainly derived from existing rotating machine industries are present on the market today (Yang, Tavner, Crabtree, Feng, & Qiu, 2012). A result of this is numerous literature sources which present reviews of techniques and methods. The reader is directed to the following referenced sources for a more detailed understanding of condition monitoring systems.

Yang (Yang, Tavner, Crabtree, Feng, & Qiu, 2012) provides a review of technical and commercial challenges related to the condition monitoring of wind turbines. The current practical challenges related to wind turbines are presented and recommendations are provided as to the research direction of condition monitoring in the wind energy industry.

Crabtree (Crabtree, Zappalá, & Tavner, Survey of commercially available condition monitoring systems for wind turbines, 2014) provides the most comprehensive review of commercially available condition monitoring. 36 commercially available condition monitoring systems are presented based on literature and contact with industry. A description of each system is given including the manufacturer, components monitored, technology for monitoring, analysis method and data sampling rate/frequency.

The following sections give a review of commercially available condition monitoring systems primarily based on the data and information provided by Crabtree as well as other sources of information in the literature.

Gearbox

It is indicated by Veers (2008, cited in (Sheng & Yang, Wind turbine Drivetrain Condition Monitoring - An Overview, 2013)) that the gearbox of a wind turbine is the most expensive component to maintain in a wind turbine over its 20 year lifetime. For this reason there are many literature studies dedicated to the condition monitoring of gearboxes in wind turbines (van Bussel, Boussion, & Hofemann, 2013; Luo, Hatch, Kalb, Hanna, & Weiss, Effective and accurate approaches for wind turbine gearbox condition monitoring, 2014; Nie & Wang, 2013; Siegel, Zhao, Lapira, Abuali, & Lee, 2014; Feng, Qui, Crabtree, Long, & Tavner, 2012; Sheng & Yang, Wind turbine Drivetrain Condition Monitoring - An Overview, 2013; Wisznia, 2013; Crabtree, Zappalá, & Tavner, Survey of commercially available condition monitoring systems for wind turbines, 2014).

Crabtree (Crabtree, Zappalá, & Tavner, Survey of commercially available condition monitoring systems for wind turbines, 2014) and Sheng (Sheng & Veers, Wind turbine Drivetrain Condition Monitoring, 2011) indicate that condition monitoring of the gearbox may be broken down into monitoring of gearbox internals, gearbox bearings and the gearbox lubrication. It is pointed out by Skriver (cited in (Feng & Tavner, Introduction to wind turbines and their reliability and availability, 2010)) that field observations show that bearings are more susceptible to failure than the gears themselves. Feng (Feng, Qui, Crabtree, Long, & Tavner, 2012) summarises the five most prominent failure modes of wind turbine gear boxes:

1. Planetary gear failure
2. Planetary bearing failure
3. ISS bearing failure
4. HSS bearing failure
5. Lubrication malfunction

Typical symptoms which may indicate an impending failure mode are given by Sheng which may include (Sheng & Veers, Wind turbine Drivetrain Condition Monitoring, 2011):

- Increased vibration
- Increased noise
- Oil contamination
- Overheating
- Performance degradation

Condition monitoring of wind turbine gearboxes is usually conducted by vibration analysis and oil monitoring. Although these are most common methods, acoustic emissions and shock pulse methods show promise. Both SCADA signals and condition monitoring signals are used to generate damage signals which can give indication to impending failure of components.

Vibration analysis is cited as being the most popular technology employed in wind turbines (Marquez, Tobias, Perez, & Papaelias, 2012) and is recommended continuously throughout operation due to the complex dynamics of wind turbines (Sheng & Veers, Wind turbine Drivetrain Condition Monitoring, 2011). This is employed not only for the gearbox, but also other drivetrain components such as the main bearing and the generator (Sheng & Veers, Wind turbine Drivetrain Condition Monitoring, 2011). From the 36 commercially available condition monitoring systems presented in the study of Crabtree (Crabtree, Zappalá, & Tavner, Survey of commercially available condition monitoring systems for wind turbines, 2014), 27 of these are vibration condition monitoring systems using accelerometers. Different sensors are utilised to measure vibrations in different frequency ranges; position transducers for low frequency, velocity sensors for middle frequency, accelerometers for high frequency and spectral emitted energy sensors for very high frequency (Marquez, Tobias, Perez, & Papaelias, 2012). Whilst there are many variants of vibration based condition monitoring systems available, many utilise the same measurement devices, however vary in number of sensors, measurement locations and analysis algorithms. Analysis of vibration is done in either the time or frequency domain in order to detect potential failures.

Whilst oil analysis is mostly conducted by taking samples whilst a wind turbine is offline, many online oil analysis condition monitoring sensors are available at a reasonable price level (Marquez, Tobias, Perez, & Papaelias, 2012). For monitoring of gearbox oil, the objective is to determine contamination and degradation of the gearbox oil (Sheng & Veers, Wind turbine Drivetrain Condition Monitoring, 2011; Marquez, Tobias, Perez, & Papaelias, 2012). Oil analysis is cited as an important condition monitoring technique as it can indicate early signs of wear and damage which may be present in the absence of vibration (Marquez, Tobias, Perez, & Papaelias, 2012). It is suggested it is a cost effective method in avoiding potentially catastrophic failures (Marquez, Tobias, Perez, & Papaelias, 2012). One method involves the counting of ferrous and non-ferrous particles that are circulated by the lubrication oil system. These particles are counted by the oil debris counter before being filtered giving indication if a fault is developing (Feng & Tavner, Introduction to wind turbines and their reliability and availability, 2010). Other parameters that may be measured include water content, total acid number, viscosity and particle element identification (Sheng & Veers, Wind turbine Drivetrain Condition Monitoring, 2011).

The shock pulse methods is identified by Marquez (Marquez, Tobias, Perez, & Papaelias, 2012) as occasionally being used by the wind energy industry as a complimentary method to support vibration measurements. It is used for condition monitoring of bearings by detecting mechanical shocks when ball or roller bearing come into contact with damage or debris.

Stress wave analysis or acoustic emissions is another condition monitoring system that is applied to wind turbine gearboxes as an additional method to vibration analysis. The analysis algorithms that are used for vibration analysis are also relevant for stress wave analysis which is an advantageous property of such a monitoring system (Sheng & Veers, Wind turbine Drivetrain Condition Monitoring, 2011). Rapid release of strain energy, such as occurs when the structure of metal is altered (frictional, strike event, propagation of crack) leads to the generation of acoustic emissions (Marquez, Tobias, Perez, & Papaelias, 2012). This method utilises stress wave sensors to monitor this release of acoustic energy in a structure. For a typical application, 5 stress wave sensors may be utilised including one on the main bearing, two on the gearbox and two on the generator (Sheng & Veers, Wind turbine Drivetrain Condition Monitoring, 2011). Stress wave amplitude histograms are analysed to give an indication as to abnormalities, damage or imminent failure of components or systems (Sheng & Veers, Wind turbine Drivetrain Condition Monitoring, 2011).

A summary of sensors, monitored parameters and outputs of condition monitoring systems is provided in Table 2. For further details of commercially available systems the reader is directed to the study by Crabtree (Crabtree, Zappalá, & Tavner, Survey of commercially available condition monitoring systems for wind turbines, 2014). For condition monitoring algorithms and signal processing methods, the reader is directed to the works of Siegel (Siegel, Zhao, Lapira, Abuali, & Lee, 2014), Marquez (Marquez, Tobias, Perez, & Papaelias, 2012) or Luo (Luo, et al., Effective and accurate approaches for wind turbine gearbox condition monitoring, 2014).

Monitorable Failure Modes	Planetary Gear Failure	Planetary Bearing Failure	ISS Bearing Failure	HSS Bearing Failure	Lubrication System Malfunction
SCADA Signals	Oil Temperature	Oil Temperature	Oil Temperature	HSS Bearing Temperature	Oil Pressure Level, Oil Filter Status
CMS Signals	LSS vibration, Non-Ferrous Particle Oil Debris Count	LSS vibration, Ferrous Particle Oil Debris Count	LSS or HHS Vibration Signals, Ferrous Particle Oil Debris Counts	HSS Vibration Signals, Ferrous Particle Oil Debris Count	
Sensors	Accelerometers, Proximity Probe, Speed Sensor (Encoder: Generator, Rotor), Temperature Sensor, Oil Particle Counter, Stress Wave Sensors, Piezoelectric Transducer				
Outputs	Vibration Spectrum (Frequency, Amplitude, Peaks), Mean Orbit of the Shaft/Misalignment (from the Proximity Probe), Temperatures, Particle Counts (Ferrous/Non-Ferrous), RPM of HSS and LSS, Power Output				

Table 2 Summary of sensors, monitored parameters and outputs of condition monitoring systems (Wisznia, 2013; Feng & Tavner, Introduction to wind turbines and their reliability and availability, 2010; Marquez, Tobias, Perez, & Papaelias, 2012)

Generator

Verbruggen (Verbruggen, 2003) and Sheng (Sheng & Veers, Wind turbine Drivetrain Condition Monitoring, 2011) highlight that vibration analysis condition monitoring techniques applied to the gearbox are also relevant to the other drivetrain components, including the main bearing and the generator. According to Sheng, a typical gearbox condition monitoring system may consist of two accelerometers attached to the generator at both the drive end and the non-drive end. Analysis techniques are similar to those described above. Based on the data presented by Crabtree (Crabtree, Zappalá, & Tavner, 2014), it is evident that condition monitoring of the generator is available in commercially available systems. Indeed, 26 of the 36 condition monitoring systems investigated in the survey contained generation monitoring systems (Crabtree, Zappalá, & Tavner, 2014).

It is indicated by Marquez (Marquez, Tobias, Perez, & Papaelias, 2012) that the condition monitoring of electrical equipment, including motors, generators and accumulators is typically conducted by measuring voltage and current parameters. For the generator, a spectral analysis of the stator current can be performed whilst the wind turbine is online, and used for detecting isolation faults in the electrical cabling.

Thermography is the process of monitoring electronic and electrical components in order to detect failure. Whilst typically this is performed when the wind turbine is offline, new camera and analysis techniques mean that this technique is suitable to online monitoring and may have application to wind turbine generators and other electronic components (Marquez, Tobias, Perez,

& Papaelias, 2012). Measurement of temperature of the rotor and stator winding is another condition monitoring technique. According to Verbruggen (Verbruggen, 2003), due to the changing loads present on the wind turbine generator, trend analysis based on parameter estimation techniques is needed for early failure or fault detection.

Tower and blade systems

Monitoring of the structural tower and blade systems, like the drivetrain components is achieved through the measurement and analysis of various sensors and signals. Despite having low failure frequency, failure of the structural components of the wind turbine can lead to large downtime and costs, combined with a reduction in generated revenue ensuring that condition monitoring of these components may be beneficial provided the sensors and systems can be included at a sufficiently low cost. Based on review of the literature, it can be determined that monitoring of structural turbine elements is conducted primarily through:

- Rotor monitoring systems
- Strain measurement and analysis
- Acoustic emission monitoring
- Ultrasonic testing techniques

Many authors identify measurement of strain through strain gauges as a method for early prediction of damage for the wind turbine structural components (Wisznia, 2013; Ciang, Lee, & Bang, 2008; Marquez, Tobias, Perez, & Papaelias, 2012; Verbruggen, 2003) suggesting it is a primary method of structural health monitoring. Liu (Liu, Tang, Han, Hu, & He, 2015) indicates this as one of only two online methods for monitoring blades (the other being acoustic emissions). Indeed, three of the condition monitoring systems in the survey by Crabtree (Crabtree, Zappalá, & Tavner, Survey of commercially available condition monitoring systems for wind turbines, 2014) contained strain gauges for blade a tower damage detection. Strain in the various components can be measured through the use of optical fibres, namely Fibre Bragg Gratings (FPGs) and associated opto-electrical instrumentation (photo-detector) (Ciang, Lee, & Bang, 2008; Wisznia, 2013). FPGs are used over foil type strain gauges for a number of reasons. They are able to be integrated into composite materials and measure very high strain as is present in stressed composite constructions. Furthermore, in addition to strain measurements, FPG distributions over a structure can be used to measure transverse crack distribution, impact events and the location of the damage in wind turbine (Ciang, Lee, & Bang, 2008). Despite the positive elements, Marquez (Marquez, Tobias, Perez, & Papaelias, 2012) suggests that although cost effective fibre optic strain sensors such as these are being developed the current cost is high. Whilst they cannot compete on a cost basis with foil type strain gauges, their other benefits as mentioned above make them more suitable in the context of wind turbine structural components.

Measurement of acoustic emissions were identified as the other potential technological option for online condition monitoring or blade and tower components (Marquez, Tobias, Perez, & Papaelias, 2012; Liu, Tang, Han, Hu, & He, 2015). Whilst this is presented by many literature sources as a potential method for condition monitoring of blades and towers (Yang, Tavner, Crabtree, Feng, & Qiu, 2012; Marquez, Tobias, Perez, & Papaelias, 2012; Ciang, Lee, & Bang, 2008; Wisznia, 2013; Dutton, et al.), this technique does not appear to be largely commercially available. Only one example was found in the survey of condition monitoring systems and it was noted this was still in the development phase (Crabtree, Zappalá, & Tavner, Survey of commercially available condition monitoring systems for wind turbines, 2014). Furthermore, Yang (Yang, Tavner, Crabtree, Feng, & Qiu, 2012) indicates that whilst acoustic emissions have potential to be useful for condition monitoring, the required high bandwidth and costly measurement and analysis techniques make it prohibitive for the wind energy industry at the current time. Although not a developed commercially available technology, condition monitoring techniques using acoustic emission is a promising emerging technology (Marquez, Tobias, Perez, & Papaelias, 2012).

Pitch and yaw systems

Literature related to condition monitoring of the pitch and yaw system is limited. It is suggested by Verbruggen (Verbruggen, 2003) that condition monitoring of the yaw system is difficult due to intermittent usage. Considering the high failure and downtime rate of the yaw system that was identified in chapter 1, this finding is unfortunate. A review of the commercially available condition monitoring systems presented by Crabtree (Crabtree, Zappalá, & Tavner, Survey of commercially available condition monitoring systems for wind turbines, 2014) find only two systems (out of 36 in the survey) with mention of the yaw system although no specific technique for monitoring is presented. For monitoring the hydraulic or electrical pitch adjustment, only one commercially available condition monitoring system (Winergy) is used for fault or failure prediction, however, once again, no indication of the technique is provided.

2. Condition based maintenance

To get an indication of the potential benefits of condition monitoring in combination with condition based maintenance and control, an impact study is performed using the ECN developed O&M tool. The impact study examines a reference wind farm in the ECN O&M tool for a baseline calculation. A second scenario is tested whereby the effect of condition based maintenance is introduced for various components. Finally, an indication of the benefit of condition based control is quantified by allowing the wind turbine to operate during the logistic and waiting phase when a maintenance event occurs. The sensitivity of the results to changes in both derating percentage of the turbine as well as the operational time after a condition signal is recorded. These analyses give the best estimate of the benefits of condition monitoring combined condition based control.

2.1 Baseline O&M model

2.1.1 Wind farm overview

For the purpose of this analysis, the default wind farm data that is available in the ECN O&M tool (version 5.0) is utilised. The major variation to the wind farm model is the replacement of the default turbine operation curve with that of a Vestas V90-3 MW machine as can be seen in Figure 9. Table 3 gives the main data parameters related to the wind farm and individual wind turbines.

For modelling the O&M costs, wind and wave data from the meteorological mast K13 site in the north sea have been used. The location of this mast can be seen in Figure 10, and is located approximately 80 – 90 km from the Dutch coast line. Weather data has been taken from this site for the period 1995 through 2004 inclusive (10 years). It can be assumed that this is the site of the wind farm in the study.

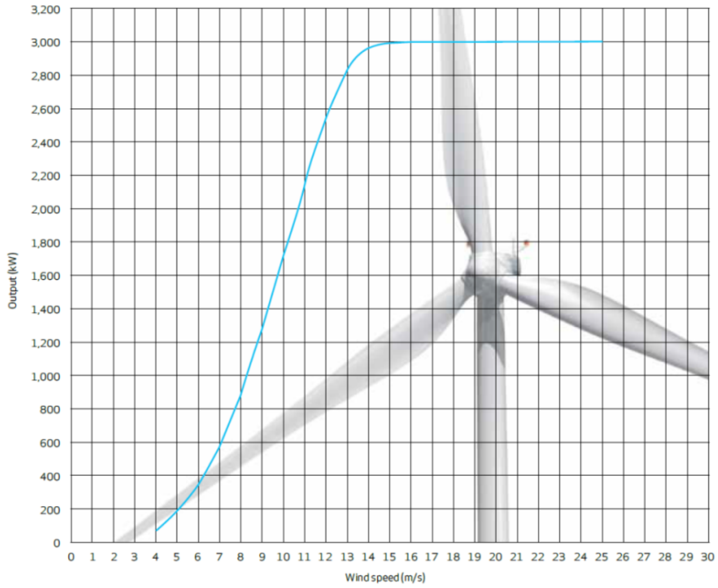

Figure 9 Vestas V90 – 3 MW Wind Turbine Operational Curve

Location	North Sea	-
Distance to Shore	85	km
kWh price	0.13	Euro
Number of turbines	130	-
Lifetime	20	years
Wind farm efficiency	0.9	-
Wind profile exponent	0.1	-
P rated	3000	kW
Investment costs	1250	Euro/kW
Hub height	80	m

Table 3 Wind Farm and Turbine Operational Data

Figure 10 Location of Meteorological Mast for Measurement of Weather Data (K13)

2.1.2 O&M strategy

This section outlines data related to the operation and maintenance of the theoretical wind farm. The following topics are covered:

- Maintenance categories
- Failure rates
- Equipment available
- Fixed costs

Information relating the maintenance categories are provided in Table 4. It can be seen that for the initial strategy, that preventative maintenance of small parts is included, however for large parts, only corrective based maintenance is employed.

The failure rates of various components are already provided in Figure 8 for the ECN O&M tool. The high failure rate (0.43 failures/year) of the generator likely suggests gearbox failures are included in this sub category. When taking into the results of the LWK survey (highest failure frequency) of onshore wind turbines in Figure 2, the combined failure rate of the generator and gearbox is 0.26 failures per year, indicating this assumption may be reasonable. Therefore this has been split in the study to the gearbox and generator. Figure 11 shows a breakdown of the likelihood of a fault type class (FTC) occurring for each subsystem or component in a wind turbine. This can be cross referenced with Table 4 to determine the details of the likelihood and severity of different repairs for components. It can be seen that repairs and maintenance are dominated in all cases (except remote resets) by the need for an inspection and small repair inside the turbine.

Maintenance categories	Fault type class classification		Type
Description	**Description**	**FTC**	
Remote reset (only downtime, no visit)	no crew, Repair = 2 hr, no costs	1	Corrective
Inspection and small repair inside	small crew, Repair = 4 hr, consumables	2	Corrective
Inspection and small repair outside	small crew, Repair = 8 hr, consumables	3	Corrective
Replacement small parts (< 2 MT) internal crane	small crew, Repair = 8 hr, low costs	4	Corrective
	small crew, Repair = 16 hr, low costs	5	Corrective
	large crew, Repair = 16 hr, medium costs	6	Corrective
	large crew, Repair = 24 hr, medium costs	7	Corrective
	large crew, Repair = 24 hr, high costs	8	Corrective
Preventive replacement small parts (< 2 MT) internal crane	small crew, Repair = 8 hr, low costs	9	Preventative
	large crew, Repair = 16 hr, medium costs	10	Preventative
Replacement large parts (< 100 MT) large external crane	large crew, Repair = 24 hr, medium/high costs	11	Corrective
	large crew, Repair = 40 hr, medium/high costs	12	Corrective
	large crew, Repair = 40 hr, very high costs	13	Corrective

Table 4 Maintenance categories used in ECN O&M tool

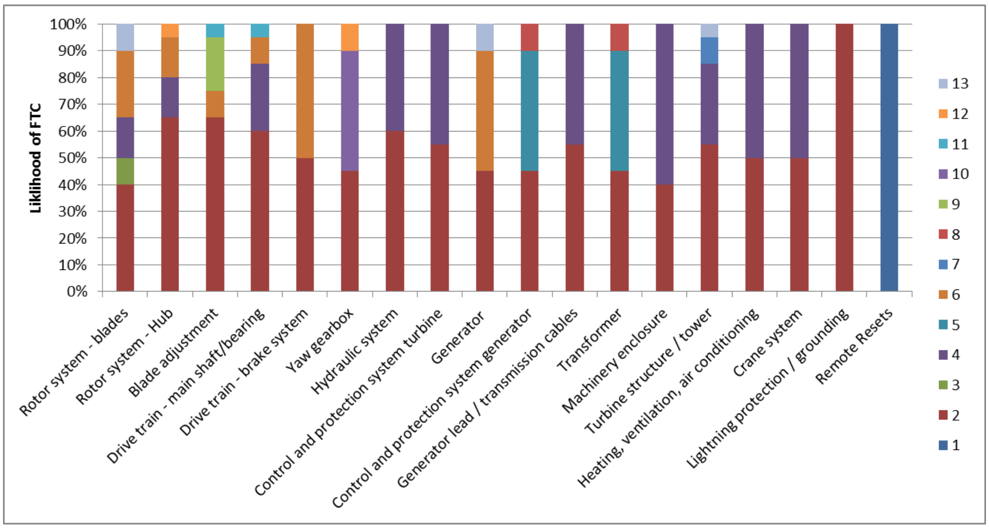

Figure 11 Likelihood of FTC occurring for each WT Subsystem/Component

In terms of equipment that is available for repairs, the baseline O&M strategy employed allows availability for three Windcats working from a mother vessel that contains an Ampelmann. Also used for maintenance are a jack-up barge, turbine crane and blade inspection unit, which have an associated cost per usage, with no fixed yearly costs. Fixed costs for the plant are broken down into regular wind turbine preventative maintenance, large wind turbine preventative maintenance and regular BOP preventative maintenance. Accounting for these leads to a yearly fixed cost of 25.3 M€.

2.2 Condition based maintenance and control model

To quantify the potential benefit of applying condition based maintenance (CBM) and condition based control (CBC), the section describes the changes made to the baseline model. Because there is no method to link load reductions and increased lifetime, this cannot be taken into account directly.

The essential difference between corrective maintenance and CBM/CBC is the ability to operate the wind turbine during the time for logistic, waiting and travel time before the maintenance can occur. For the baseline strategy, the logistic waiting time is only present of large repairs. Furthermore, the travelling distance to the wind turbine is small and thus the results may reveal a conservative estimate. Regardless though, for corrective maintenance, the plant is shut down. This study examines the resulting increase in energy yield (and the income from this) if the turbine does not have to be shut down until maintenance must be performed.

For the CBM/CBC calculation, the maintenance strategy is changed in regards to the replacement of small and large parts for the various components. The following components were identified in in Chapter 1 as being ones which may benefit from the combination of condition monitoring and active load reductions:

- Rotor system – Blades
- Rotor system – Hub
- Blade adjustment
- Drive train – Main shaft/bearing
- Yaw gearbox
- Generator

- Gearbox
- Turbine tower/structure

For these components, the corrective maintenance of small and large components is changed to CBM. A second case is also considered where only 50 percent of the corrective based maintenance activities are changed to CBM. This is likely a more realistic scenario than the first case, however at this stage only an indication as to the maximum benefit of such a strategy is sought. This alternative strategy should result in a 50 percent reduction in energy losses compared with the full CBM method which is verified by the model. The results of these studies are presented in Section 2.3.

It is noted that preventative replacement of small parts was included for in the baseline model for some components. In these cases, no changes were made to the associated components. It is also seen that not all types of failures in these components are able to be changed from corrective to condition based. Essentially, this implies that CBM can only be applied to a fraction of selected turbine components.

In addition to case studies investigating the result on increased amounts of CBM, the ECN O&M tool has been heavily modified such that account can be taken for variable wind turbine power production through modification of the P_{rated} as well as variable time that the turbine is operating during logistic and travel periods in order to determine the sensitivity to these parameters. These variables are indicated as a percentage of the maximum in both cases. The case whereby CBM is employed for 50% of maintenance activities is utilised in this analysis. The results of this analysis is presented in Section 2.3.

The power curves of the 3 MW Vestas turbines from Figure 9 are modified in the model as can be seen in Figure 12. The minimisation of the turbine P_{rated} is linked to load reduction in the turbine which can be activated when a condition monitoring symbol is received. Reductions in partial load energy yield are not considered here.

The corresponding load and power reduction allows the turbine to operate in a reduced state until the maintenance can be achieved. The modification of this power curve is important as it modifies the average power that the farm produces during logistical time. The stochastic nature of the O&M tool and the method of calculation required significant calculation time for each variation of the power curve. For this reason, the power curve is derated 2% of the original P_{rated} for each iteration.

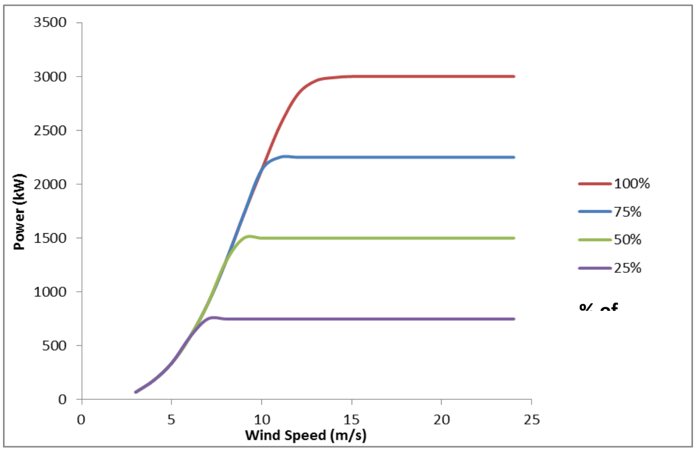

Figure 12 Power curves for four cases of reducing rated power

2.3 Results

This section outlines the results of the Baseline O&M strategy and the comparison with two alternative cases whereby CBM is employed.

2.3.1 Condition based maintenance

For clarity in the comparison of the modelled O&M strategies in this section, the following points outline the assumptions and logic employed in this subsection:

- The increase in lifetime of components through active load management cannot be quantified, as such, failure rate of components is kept constant in both cases. This may lead to under prediction of cost savings as damage and failures can propagate to cause higher failure rates in other components.
- Furthermore, the ability to derate a turbine for condition based monitoring strategies is not included in the model. This is considered in the section which follows.
- There is no ability to postpone corrective maintenance to times of preventative maintenance and as such this process cannot be modelled. Therefore, the study accepts maintenance costs stay equal. CoE reductions are solely achieved through reduced downtime of the plant.

Based on the aspects positively and negatively effecting the cost of energy in the O&M tool modelling, it can be concluded that the CBM strategy with 100% CBM for small and large components gives a reasonable estimate as to the maximum benefit that results from the proposed condition monitoring combined with load management. This will obviously differ for other wind farms with larger logistic and travel times.

An overview of the results of the modelling of the three O&M strategies is presented in Table 5. Two of the predictions outlined in the points above are immediately notable:

- Cost of repair for all three strategies is equal
- The cost saving benefit is directly proportional to the amount of corrective or condition based maintenance that is employed.

	Baseline	CBM (100%)	CBM (50%)
Availability [%-time]	92.6%	94.3%	93.4%
Availability [%-energy]	91.9%	93.9%	92.9%
Revenue losses [M€/year]	14.9	11.3	13.1
Costs of repair [M€/year]	48.0	48.0	48.0
Costs [€ct/kWh]	3.69	3.61	3.65
Total effort [M€/year]	62.9	59.3	61.1
Energy Production [MWhr/year]	1,302,133	1,329,994	1,316,064
Energy Benefit [MWhr/year]	-	27,861	13,931
Cost Benefit [M€/year]	-	3.6	1.8

Table 5 Comparison of O&M strategies

The benefits from implementing CBM are indeed notable. Availability of the plant increases 1.7% and 2.0% in terms of time and energy yield respectively. The increased availability of the plant results in a 3.6 M€/year reduction in overall cost of the plant attributed solely due to increased energy yield due to minimised downtime representing the best case scenario. For the CBM 50% strategy, the benefit is half that of the CBM 100% one. Based on the initial results, it appears that the estimation by Wiggelinkhuizen (Wiggelinkhuizen, et al., 2008) that a condition monitoring system can reduce cost of energy by 25 – 30 % is somewhat exaggerated. Furthermore, if the cost benefits (3.6 M€) are averaged per wind turbine, it is seen that the cost benefit for each installed unit is 27 k€/year when considering that a current condition monitoring system costs in the order of 14 k€ (Yang, Tavner, Crabtree, Feng, & Qiu, 2012) (not inclusive of repairs or maintenance), it is evident that the decision to include such systems seems indeed straightforward.

Figure 13 through Figure 16 show a breakdown of the downtime and the lost generating capacity for both the baseline model and the CBM (100%) model. The reduced downtime is solely attributed to the less corrective wind turbine maintenance that has to be carried out. That is, the wind turbine can continue to operate during logistic and travel events. The relative yearly downtime can be reduced by 21%, equivalent to 19617 hours over the 130 turbines in the farm through the introduction of the modified strategy. To summarise, the total reduction in downtime is significant. The increase in operational time, assuming the absence of load reductions, could lead to increased yield of 27,860 MWhr for the plant, equivalent to revenue of 3.6 M€.

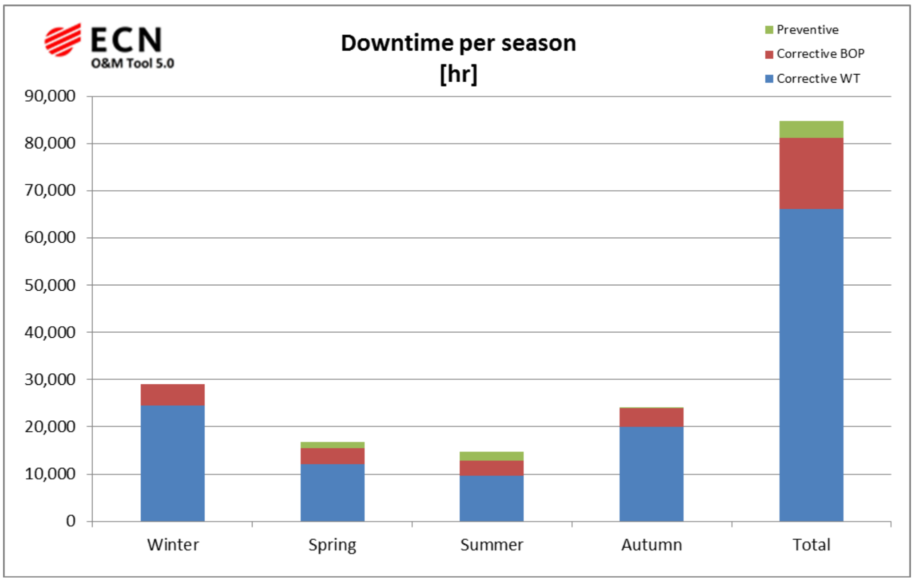

Figure 13 Breakdown of seasonally downtime for different maintenance types – Baseline Model

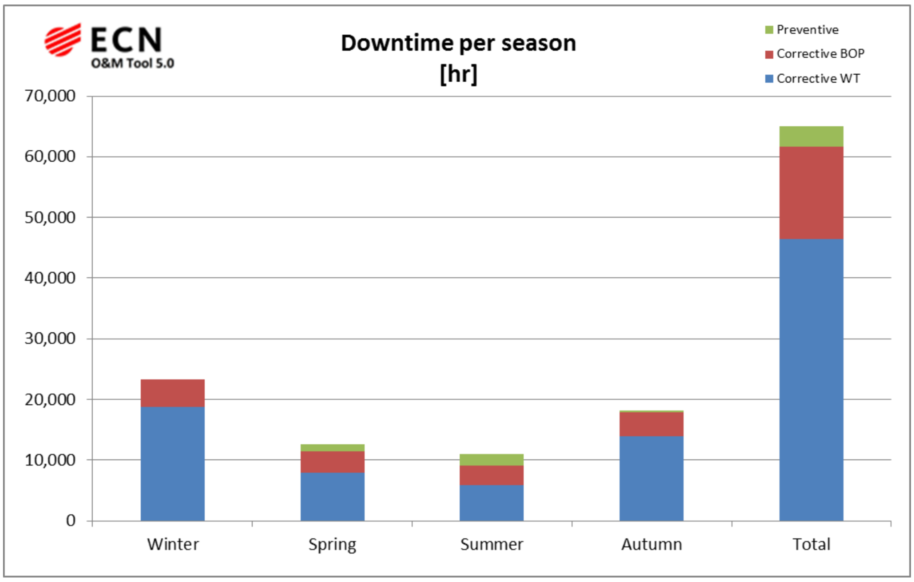

Figure 14 Breakdown of seasonally downtime for different maintenance types – CBM Model

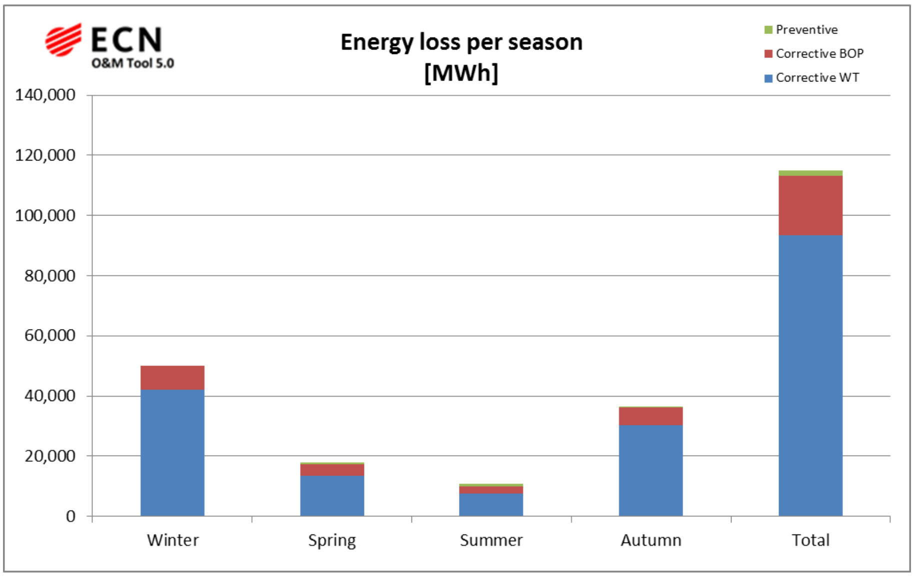

Figure 15 Breakdown of seasonally energy loss for different maintenance types – Baseline Model

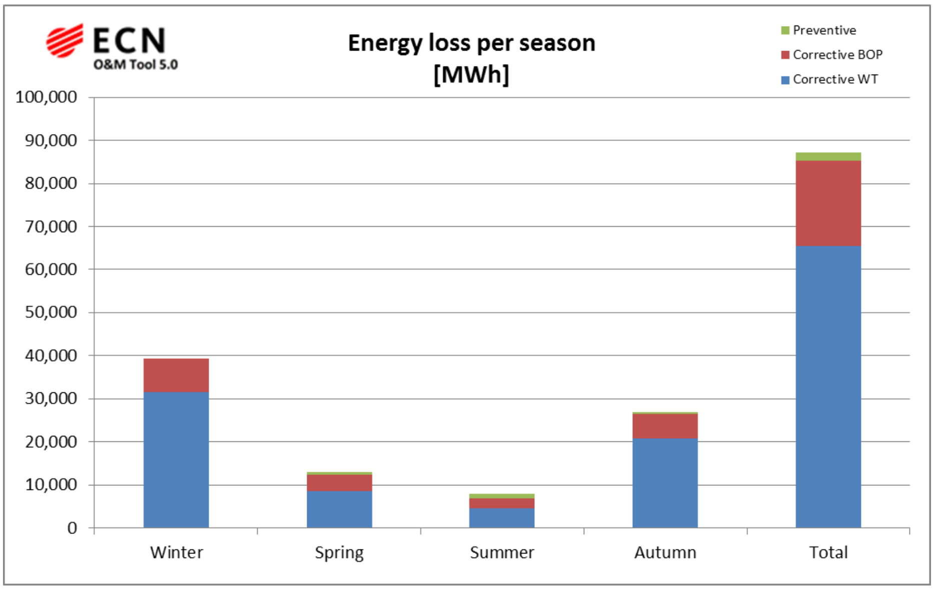

Figure 16 Breakdown of seasonally energy loss for different maintenance types – CBM Model

For the eight wind turbine subsystems which CBM was applied to, the calculated increase in energy yield and therefore revenue was calculated for the CBM 50% and CBM 100% cases. Based on the inputs for the failure frequency and the associated breakdown of the fault type classes defined in Table 4 and Figure 11, the calculated benefits are presented in Figure 17. It is evident from the figure that based on the baseline O&M tool model, the greatest gains are attributed to the blade adjustment system (1322 MWhr/953 k€). This is followed by the yaw gearbox which shows a benefit of 5785 MWhr or 752 k€. The gearbox and generator show the same benefit for given they have the same input for failure frequency and fault type class (5119 MWhr/665 k€). The blades (1322 MWhr), hub (766 MWhr), main shaft (147 MWhr) and tower (2269 MWhr) also provide significant benefit in energy yield, however are not as significant as the aforementioned four components. More analysis of these components is presented in the next section.

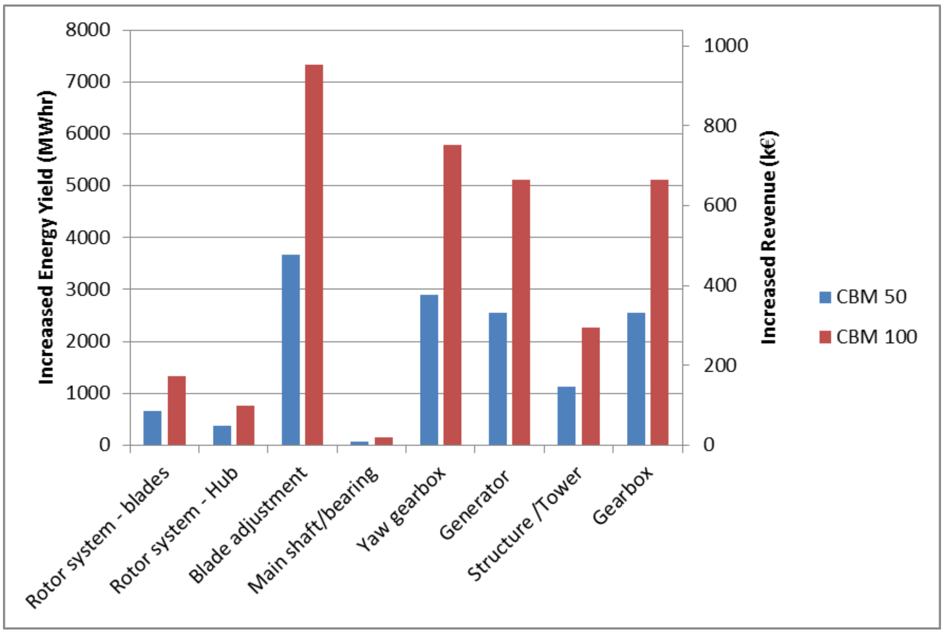

Figure 17 Increased revenue generation from modified O&M of subsystems

2.3.2 Sensitivity analysis for use in condition based control

For the current section, the case scenario result (CBM 50%) within the ECN O&M tool is taken and modified to accept batch inputs whereby the percentage of rated power, as well as the percentage waiting and logistic time can be varied to determine the sensitivity of the results to changes in these parameters. The associated function for waiting time, waiting power and mission power (as a function of mission time) are calculated for each subsequent change in the power curve.

The results of the sensitivity analysis for each component are presented in Figure 18. The results, coloured by increased energy yield, show the sensitivity of each of the components to time of operation at derated power and the derated power percentage. Similar trends are seen for each component, however there are strong variations in the increased energy yield for each, as expected based on the results from Figure 17.

It is evident by the horizontal equidistance between lines in all cases that the increased energy yield is approximately a linear function of percentage of operational time the turbine is active (assuming rated power is constant) after a condition signal is received.

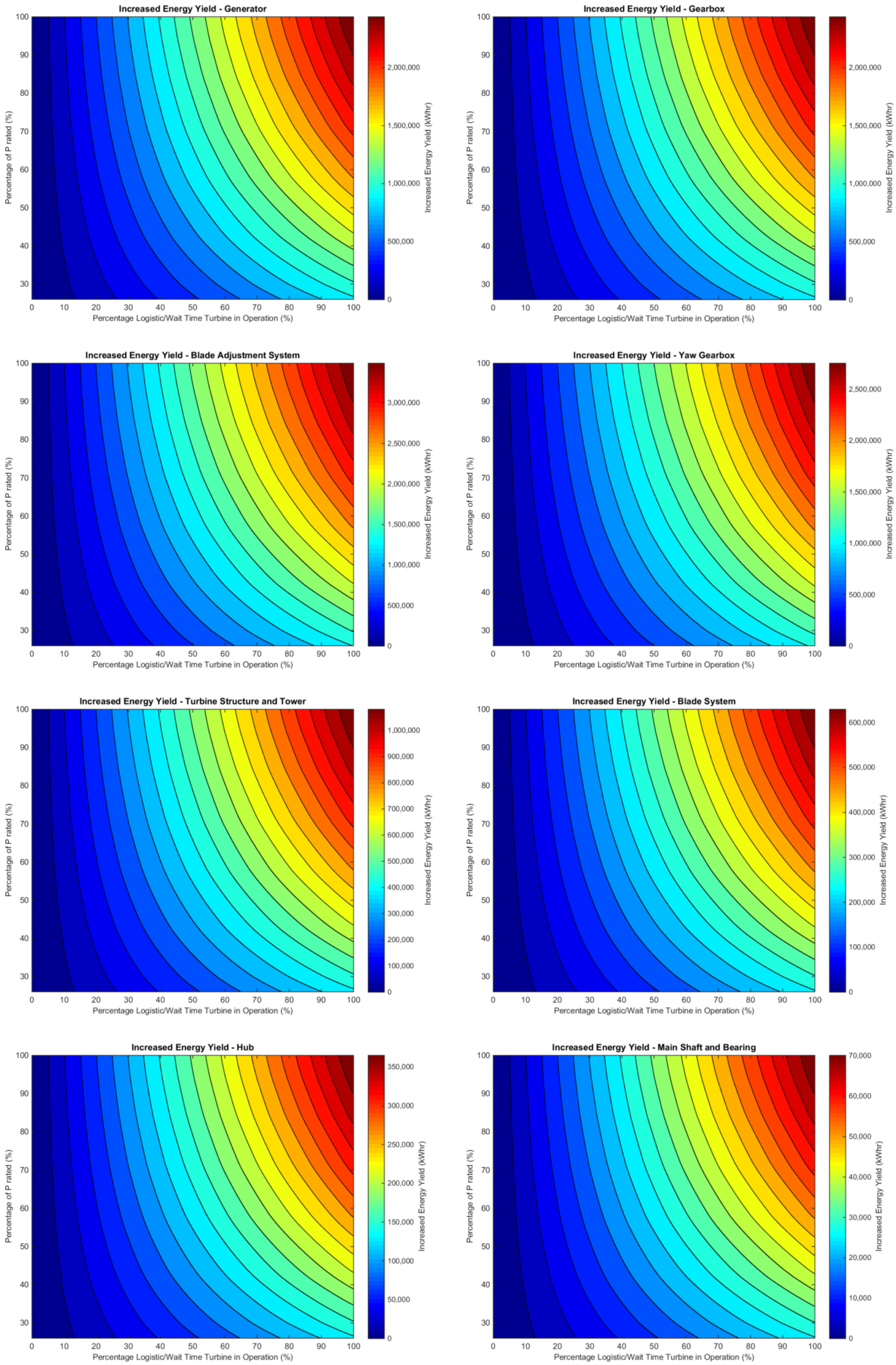

Figure 18 Increases in yearly energy yield as function of the percentage of reduced power and percentage of logistics and waiting time in operation (high increase components)

It can also be seen that the sensitivity of the yield with respect to the percentage of the logistics/wait time becomes less at lower power ratings. This could have some impact on the decision whether or not to employ condition based control. Consider the trade-off that is made with condition based control, where we reduce power to prolong the life time and increase the percentage logistics/wait time. Assume now a situation where the estimated remaining lifetime at full power is 50% of the logistics/wait time and that by reducing the rated power by 25% we can achieve a 33% in remaining life time, giving an equal total energy production. The implication of the lower sensitivity is that if there is a given (fixed) variation in the predicted remaining life time of say 5% of the logistics wait time, the variation in actually produced energy is less when we apply condition based control, than if we do not apply it.

As indicated previously for each of the components, at a constant rated power the increased energy yield is approximately a linear function of the percentage of logistic and waiting time that the turbine can operate for. Therefore, Figure 19 presents data for varying turbine rated power, assuming turbine operation during logistic, waiting and travel periods in for the selected condition based maintenance events. As expected, these show the same trend, with the increased energy proportional to the operational time.

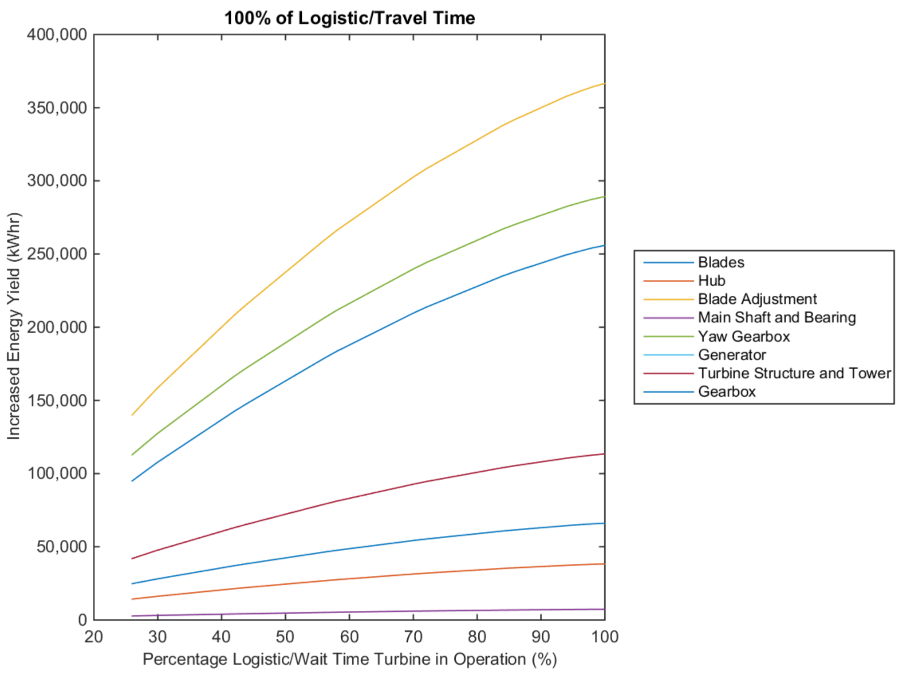

Figure 19 Increased Energy Yield from Condition Monitoring

The absolute numbers are somewhat irrelevant in terms of comparing the components which give the best overall increase in energy yield. Table 6 accompanies Figure 17 and Figure 19 in comparison of the components. Table 6 gives a brief summary of the failure frequency, sum of annual failure frequencies for condition based maintenance (product of failure frequency and probability of occurrence) and maximum increased energy yield of each of the components. It also gives a ranking of these parameters.

Identical failure and maintenance of the gearbox and generator mean that these components are the same in terms of potential extra energy yield. It is immediately evident that four of the components which condition based maintenance is applied to show increased benefit; Blade adjustment, gearbox, generator and the yaw gearbox. For the other components with the lowest increases in energy yield (turbine structure and tower, hub, main shaft and bearing and blades), absolute benefits are minimal when varying the rated power of the turbine. This suggests, for components with low failure frequencies such as these, having a high rated power is not as critical.

Component	Failure Frequency	Ranking	Sum Annual Failure Frequency (CBM)	Ranking	Increased Energy Yield (MWhr)	Ranking
Drive Train - Main Shaft and Bearing	0.014	1	0.003	1	74	1
Rotor System - Hub	0.0653	2	0.011	2	383	2
Rotor System - Blades	0.0653	3	0.016	3	661	3
Turbine Structure and Tower	0.1512	4	0.034	5	1135	4
Generator	0.4252	5	0.117	7	2559	5
Gearbox	0.4252	6	0.117	8	2559	6
Yaw Gearbox	0.5076	7	0.025	4	2893	7
Blade Adjustment	0.9779	8	0.073	6	3666	8

Table 6 Ranking the Components based on CBM 50% model

From the data presented, it is evident that the potential increase in energy yield is highly dependent on the failure frequency. Secondary to this, the amount of CBM (indicated by the sum of annual failure frequency) that can be done on that component, which has the failure, is critical. The tertiary effect is the time that these repairs eventually take, however this effect is not as pronounced as logistic, waiting and travel time are usually the dominant length of shut down times.

2.4 Benefits from condition based maintenance

Translating the increased energy yield to potential revenue benefits (assuming electricity price of 0.13 €/kWhr) shows that the maximum benefit based on the current assumption is 27,861 MWhr/year or 3.6 M€/year for the whole farm, i.e. in the range of 27 k€/turbine/year (the reference farm consists of 120 turbines). This gives further support to suggest a condition monitoring system with condition based maintenance is economically attractive, with an increase in CAPEX of approx. 14 k€ and no foreseeable OPEX costs. The potential in increased energy yield is in the range of 557 GWhr over the lifetime of 20 years (increase of 1.07%), corresponding to increased revenue of 72 M€ and a reduction of LCOE of 40 c/MWhr. This scenario is, however, overly optimistic and should be seen as an upper bound on the achievable improvement as it assumes that the condition signal is always received well in advance to enable nominal operation for the 100% of the O&M logistics and waiting time. Moreover, it is based on the CBM (100%) strategy, implying that CBM is applied for all components in the wind turbine. The calculation of a more accurate estimate of the achievable benefit requires more detailed data on the failure prediction capabilities of the condition monitoring systems, which was not available in this study. However, if strategy CBM (50%) is assumed instead, and the percentage of the logistics/waiting time in operation is reduced to 30%, the lifetime revenue increase would drop from the above-mentioned 72 M€ to 10.8 M€.

Later on, in Sections 3.1.4 and 3.2.2 the benefits from combining of CBM with condition based control will be discussed.

3. Condition based control

This chapter focuses on condition based control, aiming to further reduce turbine downtime by taking off the loads from deteriorated components. The loads reduction is achieved by operating (controlling) the turbine in a specific way, and is meant to reduce the chances of occurrence of an approaching failure, thereby delaying the failure (see Section 1.1 and Figure 1). To this end, this chapter examines what control strategies can be applied to reduce the loading on specific components of the wind turbine, while at the same time keeping the wind turbine running and not increasing loads on other parts of the wind turbine excessively.

There are some control strategies that reduce the loading with a known (additional) control effort or “cost”. These include:

- Active fore-aft tower damping – a trade-off between yaw bearing and tower loads on the one hand and an increase in pitch effort on the other hand.
- Active side-to-side tower damping – a trade-off between tower loads on the one hand and drive train loads and power quality on the other hand.
- Drive train damping – a trade-off between drive train and edge wise blade loads on the one hand and power quality on the other hand
- Individual pitch control – a trade-off between loads on the pitch, main and yaw bearings as well as main shaft bending on the one hand and pitch effort on the other hand

These techniques have so far been examined for use in normal operation and the decision of whether or not to pursue these strategies is ultimately up to the wind turbine manufacturer.

As mentioned before, the focus of this study is to examine strategies for use in case of a worsening condition and approaching failure of particular parts. Two different concepts are examined:

1. Several strategies for power down-regulation. These have the advantage that they may already be available in the existing controllers for grid support functions
2. A novel pitch actuator duty reduction strategy

As explained above, successful strategies should improve the overall energy production until failure. This means they must achieve a higher (relative) increase in the time-to-failure than the reduction in power required to achieve that increase.

3.1 Down-regulation control strategies

In this section several down-regulation strategies are derived from the nominal control strategy. Roughly speaking, a wind turbine has two different operational regions. The first region consists of operation below the rated wind speed and is referred to as partial load. The second region is called full load and consists of wind turbine operation above rated wind speed. Down-regulation strategies for both regions are discussed and their effects on the loads on different components are studied.

3.1.1 Down-regulation in partial load

In partial load, the controller generally aims to maximize the power production of a wind turbine by tracking the optimal power coefficient $C_{p,opt}$ until rated power is reached. This optimal C_p is a function of the tip-speed ratio (TSR) and the pitch angle θ. Consequently, the power production can be maximized by controlling the rotor speed through the generator torque so that the desired TSR is reached. The pitch angle is generally held constant during this process.

Down-regulation through the percentage reserve method simply consists of tracking a sub-optimal C_p, being an arbitrary percentage of $C_{p,opt}$. Since the power coefficient is a function of the TSR and the pitch angle θ, the power coefficient can be decreased by changing one or both of these parameters. Three different down-regulation strategies in partial load will now be discussed with the help of Figure 20, which depicts the contour curves of C_p as a function of TSR and θ.

The first down-regulation strategy in partial load consists of operating the wind turbine at a lower TSR, i.e., the wind turbine is operated at a lower rotational velocity at wind speeds below rated. However, as can be seen in Figure 20, the pitch angle is also increased below a certain TSR. The additional pitch action is necessary in order to prevent that the wind turbine starts operating in the stall region, which is undesirable.

The second strategy reduces the power coefficient by increasing the TSR, and thus increasing the rotor speed at lower wind speeds. As a result, the rated rotor speed is reached sooner than normal. An advantage of this strategy compared to the first strategy is that due to the higher rotor speed, more kinetic energy is stored in the rotor. If the power demand then suddenly rises again, it can be quickly met by simply increasing the generator torque. The first strategy on the other hand needs a recovery period to increase the rotor speed to the original level. In Figure 2.1 it is seen that the line for this strategy also introduces some pitching. This is done in order to prevent large deviations in the pitch angle between two consecutive wind speeds, which would occur if only the TSR was increased initially. This is because if θ is kept constant for a given TSR, this would result in operation at the left hand side of the maximum power coefficient on the $C_p - \theta$ curve. When the rated wind speed is subsequently approached and the turbine starts pitching, this would actually lead to an initial increase in the power coefficient until the pitch angle has increased enough to get on the right hand side of the optimum.

The final strategy consists of increasing the initial pitch angle in order to reduce C_p by an arbitrary percentage, while keeping the TSR constant. A disadvantage of derating through pitch control is that the response is slower compared to the first two strategies which use torque control.

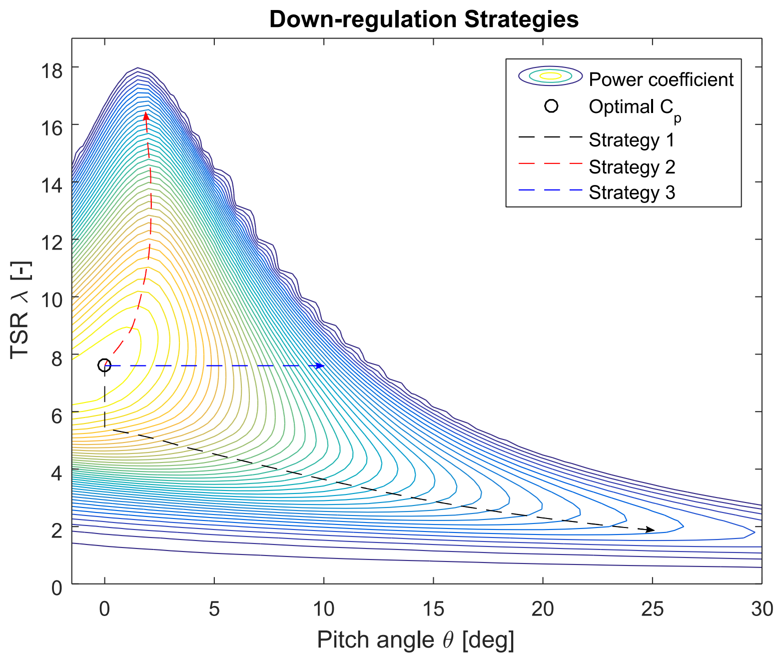

Figure 20 Contour plot of a wind turbine's power coefficient data indication three down-regulation strategies in partial load

3.1.2 Down-regulation in full load

In full load, the wind turbine operates at the rated generator torque and now the rotor is controlled at its rated value through a pitch action of the blades. In the case of down-regulation at full load, three simple methods can be applied. The first method is called de-rating and consists of decreasing the rated generator torque by a desired percentage. The second method reduces the rated rotor speed by the desire percentage. The third method consists of a combination of torque and rotor speed reduction. With respect to the dynamics of the response, the first method is preferred since this allows for a quicker recovery of the turbine's production when down-regulation is no longer required. Furthermore, if the rotor speed is reduced, the turbine will operate in a narrower rotor speed region. This means it will become difficult to derate by reducing the rotor speed for higher derating percentages, since the rotor speed cannot get lower than the cut-in rotor speed.

The effect on the loads of both torque reduction (a) and rotor speed reduction (b) in combination with the three partial load down-regulation strategies will be evaluated. As a result a total of six down-regulation strategies are implemented in the wind turbine controller. An overview of these six strategies is presented inTable 7.

Strategy	Partial Load	Full Load
1a	$TSR\searrow, \theta\nearrow$	$\tau_g\searrow$
1b	$TSR\searrow, \theta\nearrow$	$\Omega_g\searrow$
2a	$TSR\nearrow, \theta\nearrow$	$\tau_g\searrow$
2b	$TSR\nearrow, \theta\nearrow$	$\Omega_g\searrow$
3a	$\theta\nearrow$	$\tau_g\searrow$
3b	$\theta\nearrow$	$\Omega_g\searrow$

Table 7 Overview of the studied down-regulation control strategies

The different down-regulation strategies are compared to the baseline controller in Figure 21 in terms of their torque-speed and pitch angle curves. These curves are generated beforehand and are fed to the controller as references. In this case, the operating curves were computed for 20% down-regulation and by using torque reduction at full load. Similar operating curves are obtained if rotor speed reduction is applied, the only difference is then that the curves end at 80% of the rated rotor speed. Looking at the figure containing the pitch angles, it is noticed that for the second derating strategy additional pitch action is required a lot earlier than for the other down-regulation strategies. This is due to the fact that the rated rotor speed is reached relatively fast, at which point the TSR will start dropping and thus the power coefficient will increase. In order to compensate for this increased C_p, it is necessary to start pitching earlier.

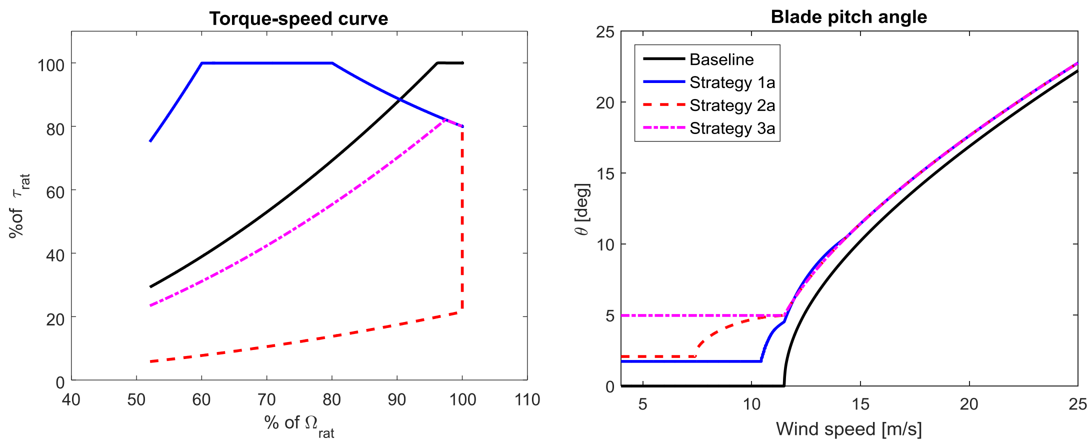

Figure 21 Torque-speed (left) and pitch angle (right) curves for the different derating strategies in combination with torque reduction at full load for 20% down-regulation

3.1.3 Loads analysis

In order to test the performance of the different controllers in terms of their load reducing capabilities, they are used in the aeroelastic simulation tool PHATAS.A desired down-regulation percentage of 20% is applied. Since the effect on fatigue loads are of primary interest, simulations are performed for normal operation with turbulent wind speeds ranging from 4-25 m/s with six realization per wind speed.

The performances of the down-regulation strategies are subsequently compared to the case of the baseline controller in terms of Damage Equivalent Loads (DELs) on a number of selected structural wind turbine components, i.e., the tower (bottom), the blade roots, the rotor shaft and yaw gearbox. It has to be noted that the results for each part are given in the resultant direction. For the tower this means that DELs of the combined motion in the Fore-Aft and Side-Side direction are computed. Additionally, the actual energy production is compared with the desired reference. The results of the simulations are presented in Figure 22-Figure 25.

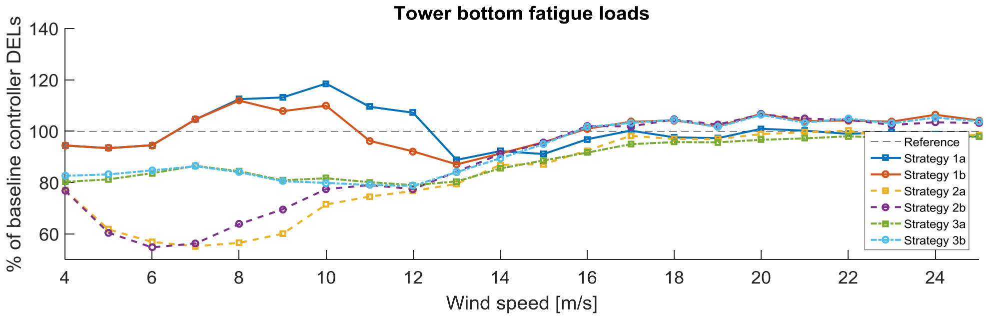

Figure 22 DELs of the tower bottom (combined FA and SS) direction as function of the wind speed

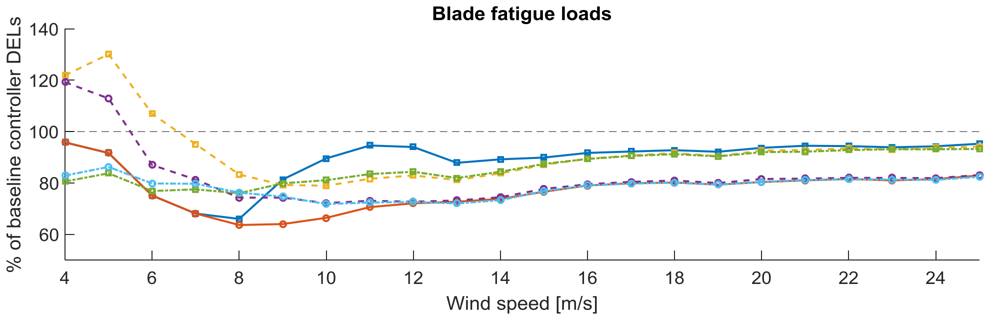

Figure 23 DELs of the blades as function of the wind speed

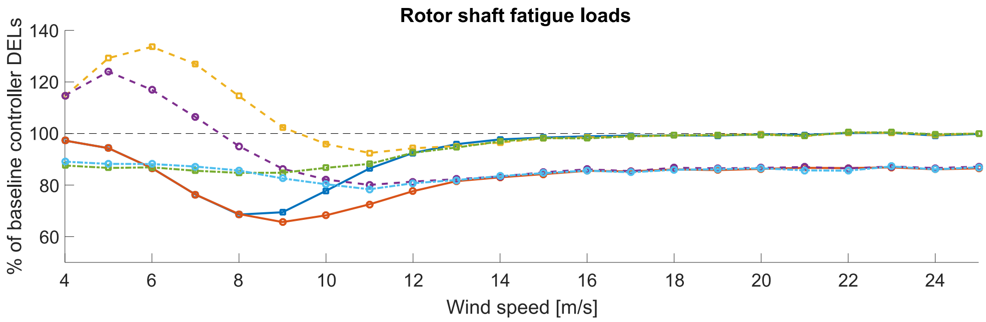

Figure 24 DELs of the rotor shaft as function of the wind speed

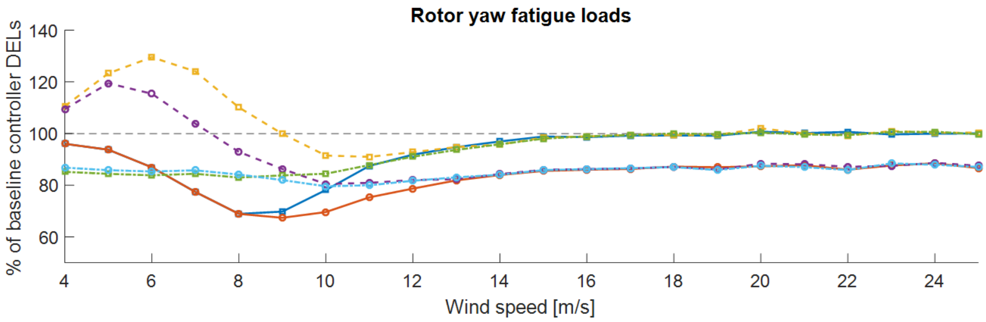

Figure 25 DELs of the rotor yaw moment as function of the wind speed

The effects of the different down-regulation strategies on tower loads are depicted in Figure 22. It can be observed that there is an increase in fatigue loads at wind speeds around 10 m/s when down-regulation strategies 1a and 1b (TSR↘) are used. The reason for this increase in fatigue loads is that by reducing the TSR these strategies operate the turbine at the cutin rotor speed for longer periods of time than the baseline controller. However, around the cutin rotor speed, the tower frequency gets excited by the 3p frequency, leading to increased oscillations and, hence, fatigue.

Another interesting observation from Figure 22 is that strategies which reduce the rated rotor speed at full load ("b") result in slightly higher tower fatigue loads than in the case of reducing the torque. The increase in fatigue loads when the rated rotor speed is decreased, is thought to be the result of a decrease in aerodynamic damping. Aerodynamic damping results from the motion of the rotor blade relative to the wind velocity, thus this effect is reduced when the relative velocity is decreased. Furthermore, when the rated rotor speed is reduced the turbine requires a larger pitch action when operating in full load. This reduces the effective blade area and thus also results in a decrease of the aerodynamic damping and hence an increase in fatigue loads.

Figure 23 shows increased fatigue loads at very low wind speeds for strategy 2a and 2b. This is because the turbine operates at higher rotor speeds compared to the nominal controller at these wind speeds. This is also seen at higher wind speeds, when the strategies that limit the rotor speed show a larger decrease in blade loads. However, even the three strategies that reduce the generator torque at full load result in a (smaller) decrease of blade fatigue loads at higher wind speeds.

In Figure 24 it can be observed that the rotor shaft DELs increase at wind speeds around $V = 6$ m/s when using derating strategies 2a and 2b. This is due to the higher rotational velocity of the rotor which results in higher bending moments of the blades. In turn this also leads to higher bending moments and thus fatigue loads in the rotor shaft. At higher wind speeds it is observed that reducing the maximum rotor speed has a positive influence on the fatigue loads on the shaft, while reducing the maximum generator torque results in similar loads as in the case of the nominal controller. The same conclusions can be made with respect to the rotor yaw loading (Figure 25).

Finally, the lifetime loads are investigated. Using the Weibull distribution, the lifetime fatigue loads of several turbine components are computed for each derating strategy and compared to the fatigue loads resulting from the nominal controller. For a clear comparison it is assumed that the down-regulation strategies are used for the entire lifetime of a turbine. The results of this analysis are presented in Table 8.

	Strategy 1a	**Strategy 1b**	**Strategy 2a**	**Strategy 2b**	**Strategy 3a**	**Strategy 3b**
Tower bottom	+1.8%	-0.2%	-17.6%	-12.7%	-13.2%	-9.1%
Blade roots	-8.9%	-25.1%	-14.6%	-24.0%	-14.2%	-24.8%
Rotor shaft	-4.9%	-17.9%	-0.9%	-14.2%	-4.2%	-15.9%
Rotor Tilt	-5.4%	-18.3%	-0.9%	-14.4%	-4.7%	-16.2%
Rotor Yaw	-5.5%	-17.3%	-1.3%	-13.8%	-4.8%	-15.4%
Energy production	-17.1%	-20.1%	-20.8%	-20.3%	-20.3%	-20.7%

Table 8 DELs of several structural wind turbine components relative to the performance of the baseline controller

3.1.4 Benefits from condition based control by down-regulation

The presented loads analysis indicates that the investigated down-regulation strategies generally reduce the fatigue loading on the turbine components. For condition based control, the most beneficial strategy depends on the deteriorated component that needs to be operated at reduced loading. From Table 8 DELs of several structural wind turbine components relative to the performance of the baseline controller, it becomes clear that strategy 1b (operation at reduced TSR in partial load, and reduced rated rotor speed in full load) has most pronounce impact on the lifetime loads on most components, which suggests that strategy to be the first choice. However, Figure 22 indicates that for wind speeds below rated the tower loads may increase substantially, and therefore depending on the current wind conditions this strategy may not be desirable. In partial load, strategy 2b has higher tower load reduction potential, but the loads on blades and shaft are worse. Therefore, the strategy selection depends on the component of interest and the wind conditions.

In Section 2.3.2 a number of components were identified that have high potential for achieving economic benefits when condition based maintenance and control is applied to them:

- **Generator**: with respect to the generator , down-regulation in combination with a lower electric torque seems the most suitable strategy. This corresponds to **Strategy 1a** (operating at decreased tip speed ratio [and lower torque] below rated, and reduced rated torque above rated). This strategy may increase tower loads at below rated wind conditions somewhat, but the other loads remain lower.
- **Gearbox**: all strategies involving reduction of the rated rotor speed (Strategies 1b, 2b and 3b) in full load result in lower loads on the shaft. In partial load, however, 2b does not perform well as it increases the loads on the shaft for some wind speeds. **Strategy 1b**, or alternatively 3b, are preferable with respect to the reduction of loads on the gearbox. If the largest possible load reduction is aimed (especially in partial load), then strategy 1b should be used. Between 8 and 10 m/s, the load reduction is around 30%! However, if the loads on the remaining components is considered important as well (and particularly the tower loads), **Strategy 3b** becomes the best option.
- **Yaw gearbox**: from the components analyzed, the rotor yaw moment is most closely related to the load on the yaw gearbox. Similar discussion hold here as for the gearbox, suggesting **Strategy 3b** as preferred option.
- **Pitch mechanism**: all power down-regulation strategies, considered in this section increase the pitch actuator duty cycle because the rotor speed control by blade pitching starts at lower wind speeds compared to the normal operation. Some of the strategies reduce the blade loads significantly, but it is not straightforward to translate these benefits into loads reduction on the pitch mechanism. Loads on the pitch mechanism are explicitly targeted using another condition control strategy, discussed in the next section.

To quantify the benefits of condition based control in terms of increased power production, the sensitivity study in Section 2.3.2 will be used. Furthermore, we will assume that condition based control increases the time to failure of a certain component by a factor inversely proportional to the DEL reduction achieved for that component to the power of M, M being the material exponent in the inverse power law model relating life L to stress S, $L = 1/kS^M$. For steel, M=4 is typically used, meaning that a 16% DEL reduction is translated into 2 times longer life ($1/(1-0.16)^4$). From Table 8 and the discussion above it seems reasonable to assume that condition based control can achieve 16% reduction of fatigue loads on gearbox and yaw mechanism, thereby prolonging the time to failure by a factor of two.

Assume now a situation where the estimated remaining time to failure at full power is 30% of the logistics/wait time and consider the sensitivity plots in Figure 26 below (same as those in Figure 18 but provided here again for more convenience). This situation is represented by the red diamonds in the figure. By doubling the time to failure, and hence the percentage of logistics and waiting in operation at reduced power (80%), we move to the green diamonds, increasing the energy yield by over 595 MWh/year (from 714 MWh to 1309 MWh) for the gearbox or, assuming 130 €/MWhr, over 1.5 M€ throughout the lifetime of 20 years. For the yaw gearbox the energy yield increase is around 655 MWh/year, which boils down to over 1.7 M€ in 20 years. In combination with CBM, the total benefit is over 3.4 M€ (1309 MWh) for the gearbox, and over 3.7 M€ for the yaw gearbox.

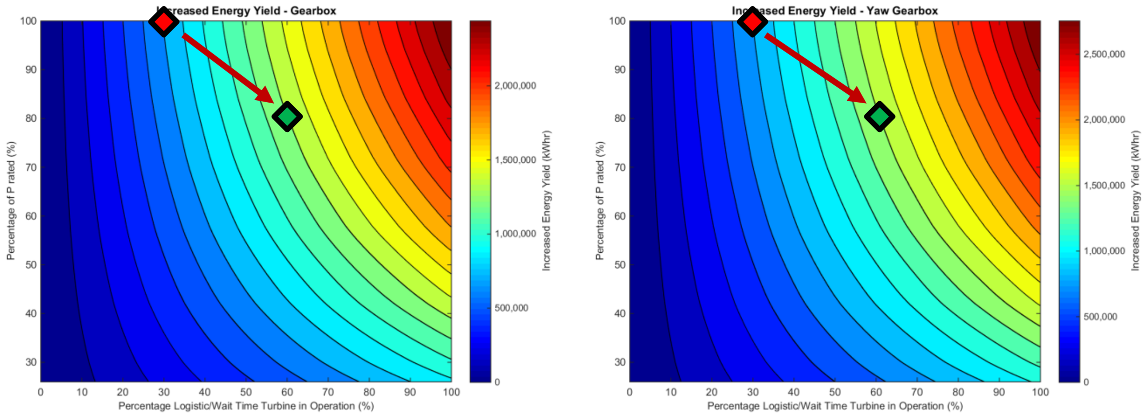

Figure 26 Increases in yearly energy yield as function of the percentage of reduced power and percentage of logistics and waiting time in operation for the gearbox and yaw gearbox

3.2 Pitch actuator duty reduction control strategy

In Section 3.1, down-regulation control strategies were investigated and shown to be beneficial for condition based control with respect to some of the turbine components, namely the generator, the gearbox and the yaw gearbox. However, these were argued to have a negative (undesired) impact on the pitch duty cycle as the blades start pitching at lower winds to derate the turbine. In this section, an alternative approach for condition based control is developed that targets the pitch systems specifically. The pitch system is important to consider with condition based control as it causes the highest number of incidents and significant down time (see Figure 6).

3.2.1 Method description and simulation results

The idea proposed here is to reduce the pitch activity by using the generator torque to assist the pitch control loop in controlling the rotor speed. The generator torque is only allowed to vary up to some maximum allowed torque and the rotor speed is allowed to vary in a margin around the rated rotor speed. Once the rotor speed exceeds this margin, pitch is used to return the rotor speed to within the assigned rotor speed margin, after which the generator torque control takes over the rotor speed regulation again.

Figure 27 shows the behavior of the reduced pitch algorithm using scaled pitch angle, generator torque and rotor speed signals (all normalized). As mentioned, the rotor speed is controlled with the torque within a predefined rotor range. Pitching is reduced to the moments when the rotor speed leaves this range or when the generator torque reaches its maximum torque. For instance,

just before the 500 seconds into the simulation, the rotor speed drops below rated rotor speed – 1 rpm, and the controller reduced the pitch angle. Pitching stops once the rotor speed has recovered sufficiently. Just after 530 s, the rotor speed is increasing above rated and now the torque hits its maximum value. Pitching starts once the maximum generator torque is achieved and stops once the rotor speed is at the same value at which maximum torque was achieved.
Simulations were run with the generator torque allowed to vary up to 10% above rated torque. The margin on the change of the rotor speed at which pitch control takes over is varied from 0.2 rpm to 1.0 rpm to study its effect on the achievable performance. Figure 28 shows the standard deviation of the power for various ranges of rotor speeds for which torque supports the rotor speed regulation. Figure 29 shows standard deviation of the rotor speeds. Figure 30 and Figure 31 show the effect on the power production and the pitch duty cycles, respectively. Finally, Table 9 and Table 10 show the results in terms of fatigue load and duty cycle reduction.

The simulations show that targeting the pitch effort with this specific strategy results in an average 54% reduction of the pitch effort at the cost of 7% reduction in power production. That means that a 7% reduction in produced power can be used to achieve a doubling in the remaining time until failure and thus up to an 102% ((100%-7%)/46%) increase in overall energy production.

It should also be noted that it is possible to combine the pitch control strategy with one of the other power reducing strategies to give sufficient headroom in terms of maximum torque, power or rotor speed. However, this would result in a lower overall energy production (Figure 30).

This particular condition control strategy comes at the expense of larger power fluctuations in full load and requires some margin in terms of maximum torque and power relative to rated conditions. Furthermore, the loads on the main shaft increase somewhat due to the increased torque actuation (see Table 9).

It should be noted that although the power fluctuations are larger than for a wind turbine operating in full load, the fluctuations are in a similar order of magnitude as in near rated conditions and the averaged effect over a farm will be very limited as only wind turbines with poorly pitch systems would be using it.

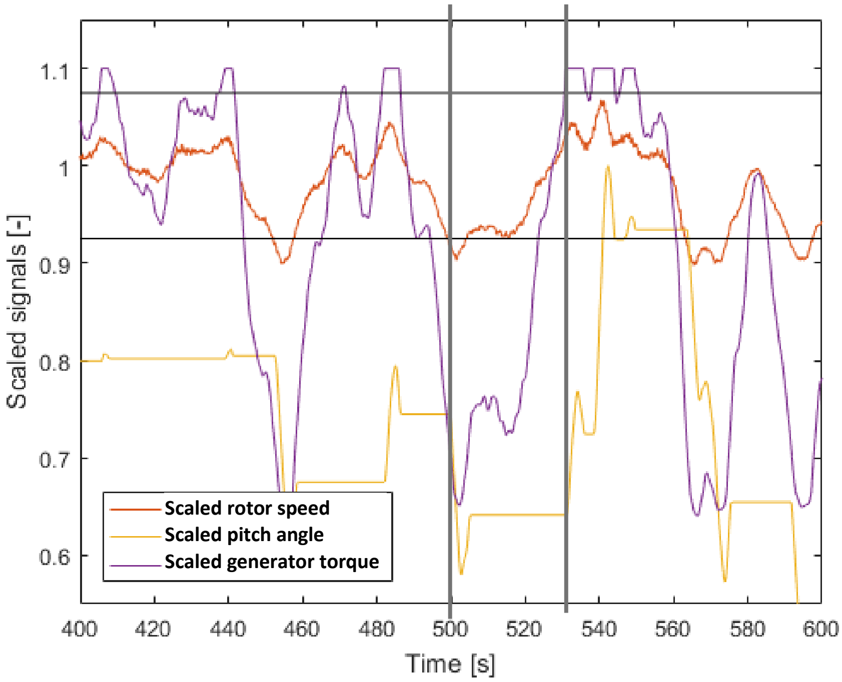

Figure 27 Reduced pitch algorithm behavior

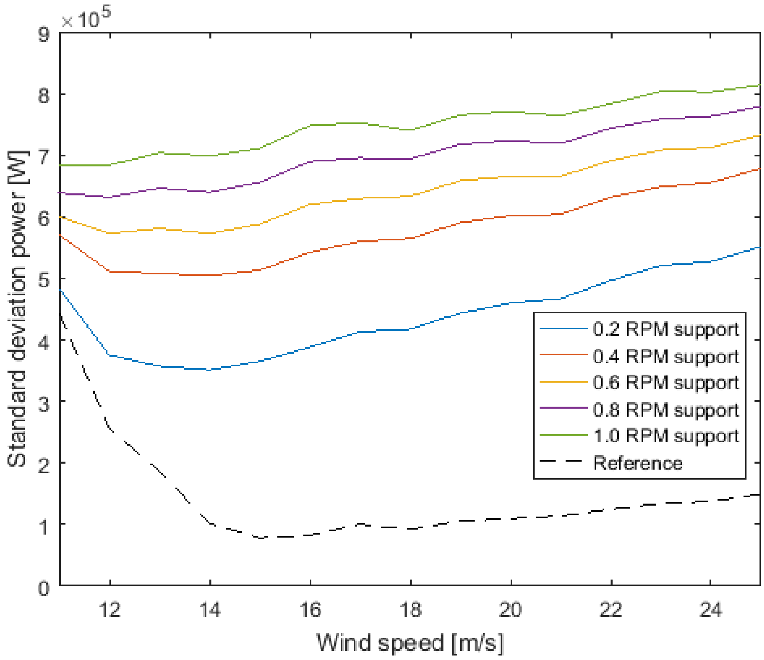

Figure 28 Standard deviation of the power for the reference case and various ranges of rotor speed torque support

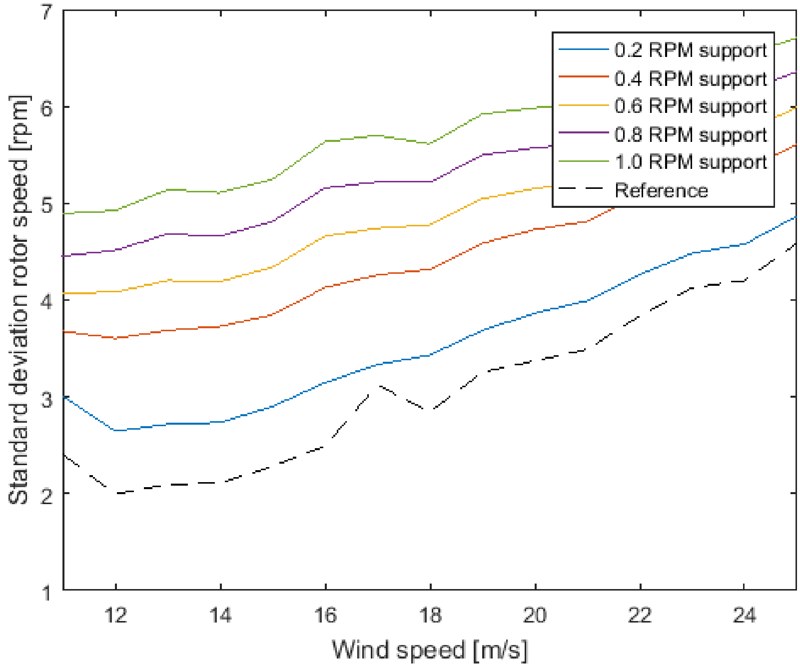

Figure 29 Standard deviation of the rotor speed for the reference case and various ranges of rotor speed torque support

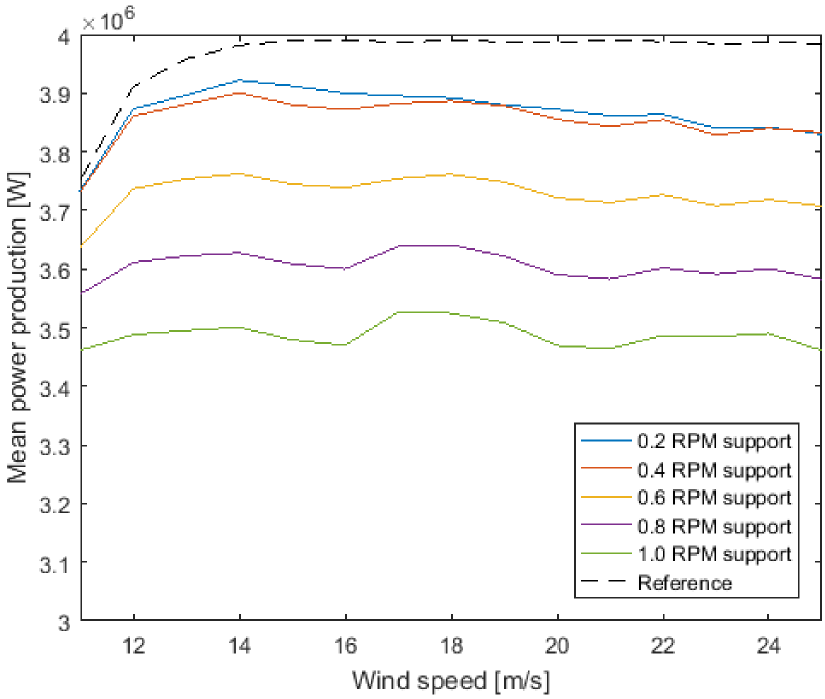

Figure 30 Effect on power production due to pitch limiting behavior

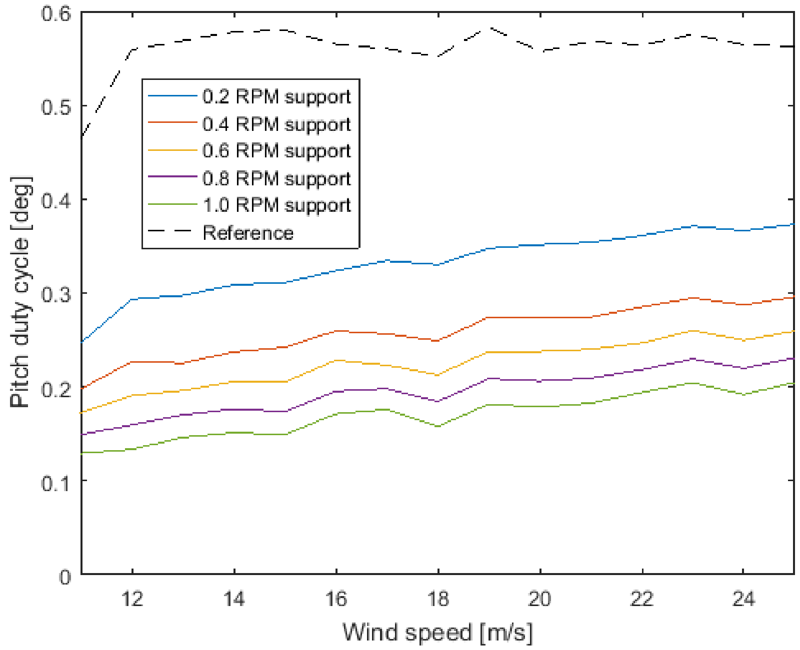

Figure 31 Effect on pitch duty cycle

	Reduced pitch Strategy
Rotor – flapwise	0.9579
Rotor – leadwise	1.0044
torque on drive train support	1.1532
Main shaft - yaw loading	0.9951
Main shaft – tilt loading	0.9858
Tower – fore aft	0.9672
Tower – side to side	0.9765

Table 9 Reduced pitch in full load: fatigue loads (Weibull weighted)

	Reduced pitch strategy
Generator	1.00
Pitch activity	0.46

Table 10 Reduced pitch in full load: generator and pitch activity, wind speeds 14-25 m/s

3.2.2 Benefits from condition based control by pitch reduction control

As explained above, the new condition based control strategy based on reducing the blade pitch activity results in up to 54% reduction of the pitch effort at the cost of 7% reduction in power production. That means that a 7% reduction in produced power can be used to achieve a doubling in the remaining time until failure and thus up to an 102% ((100%-7%)/46%) increase in overall energy production.

Similar to Section 3.1.4, assume again a situation where the estimated remaining time to failure at full power is 30% of the logistics/wait time and consider the sensitivity plots in Figure 32 below. This situation is represented by the red diamond in the figure. By doubling the time to failure, and hence the percentage of logistics and waiting in operation at reduced power (93%), we move to the green diamond. This represents an increase the energy yield by about 1050 MWh/year (from 1050 MWh to 2100 MWh) for the pitch mechanism. Assuming 130 €/MWhr, the improvement boils down to over 2.7 M€ throughout the lifetime of 20 years. In combination with CBM this benefits totals at around 5.5 M€.

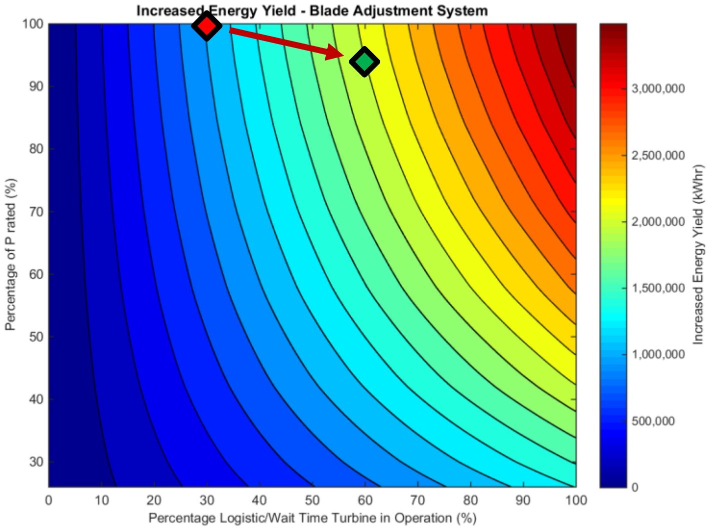

Figure 32 Increases in yearly energy yield as function of the percentage of reduced power and percentage of logistics and waiting time in operation for the pitch mechanism

4. Conclusions

The main idea behind condition based control is that the controller is adjusted to reduce the loads on a part with a deteriorating condition, with the aim of delaying failure and increasing the total energy produced until the moment of failure. The benefit of applying condition based control is primarily in terms of increase of the energy yield, although secondary benefits may also exist.

The O&M case study presented here established an improvement of as much as 2% of the farm availability if a condition based monitoring system is employed. For the reference wind farm considered in this study, this boils down to a revenue increase of 72 M€ over the lifetime of the farm. However, this figure represents an upper limit on the achievable benefit as it is based on an ideal scenario. More specifically, it is computed by assuming that CBM is applied to all turbine components (CBM 100% strategy) and that the condition signal is always received enough in advance of the actual failure to allow for performing the O&M planning and waiting activities before the actual failure occurs. The calculation of a more accurate estimate of the achievable benefit requires more detailed data on the failure prediction capabilities of the condition monitoring systems, which was not available in this study. However, if strategy CBM (50%) is assumed instead, and the percentage of the logistics/waiting time in operation is reduced to 30%, the lifetime revenue increase would drop from the above-mentioned 72 M€ to 10.8 M€ (availability increase by 0.3%).

The benefit of condition based control (in terms of yield) depends greatly on which parts fail most and whether for those parts a suitable condition based control strategy can be designed. Looking at the benefits in terms of energy yield only, condition based control is only worthwhile if the failure can be delayed significantly more than the reduction in power to achieve delay and if other trade-offs in terms of loading are acceptable. A relation between loading and remaining life time has to be assumed to be able to calculate the benefit. The assumed relation is that the time to failure is inversely proportional to the DEL reduction achieved for that component to the power of M, M being the material exponent in the inverse power law model relating life L to stress S, $L = 1/kS^M$.

In this report, two condition based control methods have been investigated: power down-regulation and a novel pitch reduction control. Both methods deliver fatigue load reductions at the expense of some power loss, but are complementary as they target different components. Power down-regulation is shown capable of doubling the time to failure in the gearbox and the yaw mechanism at the cost of 20% less power production and some increase in the pitch loading. The pitch reduction strategy, in turn, doubles the time to failure in the pitch mechanism at the price of

7% less power and 15% higher load in the drive train. Depending on the detected component degradation, the most suitable strategy can be selected.

In terms of economic benefits, significant revenue improvements are estimated for condition based control, ranging from 1.5-1.7 M€ (for the gearbox and the yaw mechanism) to 2.7 M€ (for the pitch system). Notice that these come on top of the benefits from CBM In terms of economic benefits, significant revenue improvements are estimated by combining condition monitoring systems and condition based control, ranging from 1.5-1.7 M€ (for the gearbox and the yaw mechanism) to 2.7 M€ (for the pitch system). This sums up to a total of 5.9 M€ additional revenue. This benefit is solely due to an increased availability by 0.17%. This benefit comes in addition to those from CBM, so that a total of 0.47% increase in availability is obtained.

It should be investigated whether the assumptions that have been made are accurate. In particular, the assumption on the relation between loading and remaining lifetime should be investigated for different parts and failure mechanism.

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