PROJECT DELIVERABLE REPORT

OPTIMUS

Demonstration of Methods and Tools for the Optimisation of Operational Reliability of Large-Scale Industrial Wind Turbines

Collaborative project

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Authors: Fausto Pedro Garcia Marquez (UCLM), Diego Pedregal (UCLM), Mayorkinos Papaelias (UoB), Stuart Hillmansen (UoB), Jun Zhou (UoB), Pietro Tricoli (UoB), Gerard Fernando (UoB), Spyridon Kerkyras (Feldman Enterprises), Alexandros Karyotakis (TERNA Energy), O. Panagoiliopoulos (TERNA Energy), V. Karakassidis (TERNA Energy), Jose Enrique Camacho Questa (INGETEAM), Luis Moreno (INGETEAM), Chantal Roldán De La Cuadra (INDRA), Miguel Murillo Calleja (INDRA), Paul McKeever (NAREC), Christian Little (NAREC)

Dissemination Level (PU/PP/RE/CO): PU

Project coordinator: Paul McKeever, NAREC

Tel: +44 (0) 1670 357613

Fax: +44 (0) 1670 359666

E-mail: paul.mckeever@narec.co.uk

Project website address: www.optimusfp7.eu/

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Summary

In this deliverable report the consortium has collected, analysed and evaluated the information available on existing commercial, pre-commercial and research-based condition monitoring systems with respect to their technical characteristics, efficiency, reliability, cost and easiness of installation on non-instrumented wind turbines. At the same time, the operational requirements set by wind turbine manufacturers and operators for the minimisation of occurrence of faults and failures have been assessed and are presented in this report. The efficiency and reliability of existing systems have been compared with the operational requirements as these have been set by wind turbine operators and manufacturers in order to optimise wind turbine operation. The results that have been presented in this report have been taken into account in order to ensure that a substantial step-change in the efficiency and reliability of wind turbine operation will be realised and demonstrated by the end of the OPTIMUS project.

1. Introduction

Wind energy is the most important renewable energy source at global scale. Many studies predict that the growth of wind energy will continue rising until at least 2030 [1-5]. The size of wind turbines (WTs) will continue to grow, thus requiring more cost-effective operations based on optimised levels of reliability, availability, maintainability and safety. The operation and maintenance (O&M) costs can be 20%–30% of the total investment costs of the project over its lifetime. Although larger turbines may reduce the O&M costs per unit power, the cost per failure is increasing. By employing a suitable condition monitoring or inspection technique, many faults can be detected and controlled in operational conditions. Early detection of incipient faults prevents major component failures and allows the implementation of predictive repair strategies. Therefore appropriate actions can be planned in time to prevent major failures, which would result in significant O&M costs and downtimes to be incurred [6].

Some components fail earlier than expected and cause unscheduled downtimes adversely affecting the overall success of utility-scale wind energy projects [7-13]. Condition monitoring systems (CMS) can contribute to the improved operational control of the main components. CM is usually used to collect the main parameters of the WTs' components, e.g. gearbox, generator, main bearings, blades, tower, etc. CM together with advanced mathematical methods can provide continuous information of the component status based on techniques as vibration and oil analysis, thermography, strain, acoustic emission, etc. [14]. There have been several research studies which have sought to improve the current mathematical methods employed in CMS [14-25].

The main components of the WTs are illustrated in Figure 1. The blades, connected to the rotor via the hub, are moved by the wind. The rotor transmits the mechanical energy via the low speed shaft through the gearbox to the high speed shaft, ending in the generator. The low speed shaft is supported by the main bearing. The alignment to the direction of the wind is controlled by a yaw system that turns the housing (or "nacelle") for that purpose. The nacelle is mounted at the top of a tower, and the tower is assembled on a base or foundation. The pitch system (mounted in each blade) is a mechanism that turns the blade to controls the wind power captured, and it can be employed as an aerodynamic brake. The WT has also a hydraulic brake to stop the WT. The meteorological unit, or weather station, provides the weather data (e.g. wind speed and direction) to the control system and it leads to control the pitch system, the brake, the yaw system, etc.

Although larger turbines may reduce the O&M cost per unit power, the cost per failure is increased. Condition monitoring and fault diagnosis of wind turbines has thus greater benefit for such situations [26]. With good data collection and appropriate signal analysis methods, faults can be identified while components are operational and actions can be planned in time to prevent further damage or failure of components, resulting in improved reliability and availability [14].

Central control systems which continuously monitor the performance and operation of every wind turbine have been adopted by most modern wind farms [26]. García Márquez, Tobias et al. [14] reviewed vibration analysis, acoustic emission and other state-of-the-art condition monitoring techniques of wind turbines. Furthermore, García Márquez, Tobias et al. [14] pointed out that, in addition to the technique, the capability of a condition monitoring system depends on two basic elements: the proper type and distribution of sensors, and the associated signal processing methods utilised to extract key information from complex signals.

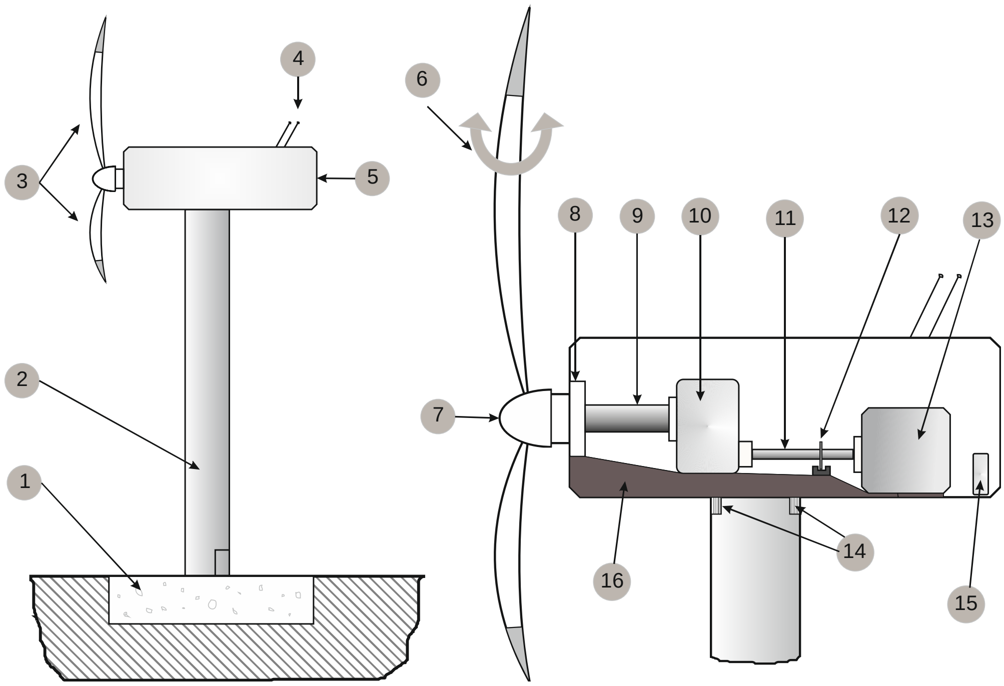

Figure 1: Components of the WT: 1-Base/Foundations; 2-Tower; 3-Blades; 4-Meteorological unit (vane and anemometry); 5-Nacelle; 6-Pitch system; 7-Hub; 8-Main bearing; 9- Low speed (main) shaft; 10-Gearbox; 11- High speed shaft; 12-Brake system; 13-Generator; 14-Yaw system, 15-Converter, 16-Bedplate. N.B. Drive train = 9+11.

The wind turbine gearboxes have always been a source of concern due to the large downtimes their failure can cause as well as the high costs associated with their repair and replacement. In the early days of industrial wind turbines most problems with gearboxes arose from design deficiencies resulting in frequent and costly failures. Although improvements have been made in gearbox designs in recent years largely thanks to the introduction of internationally recognised standards, gearbox reliability remains a problem.

There are still instances in multi-MW WTs where poor design remains the primary factor for early failure and replacement of certain gearboxes. Variable loads caused from wind turbulence and changes in the wind speed also contribute in the evolution of damage in gearbox components, particularly bearings and gears.

Certain turbines are expected to have three to four different gearboxes over a twenty year lifetime. With gearboxes costing up to 10% of the total price of a WT including installation costs, their reliability becomes of critical concern to the wind energy industry. Gearbox problems can hamper the financial success of certain wind energy projects limiting the possibilities for a number of future projects. Furthermore, higher O&M costs can lead to higher electricity costs which are passed on to the consumer.

Misalignment can cause fatigue damage to initiate earlier than expected and is very difficult to predict. Vibration analysis is the primary methodology for monitoring the operation of gearboxes. Depending on the signal processing methodology employed the value of the data acquired may change dramatically.

Power converters are a critical component of modern WTs and their failure can result in unnecessary downtimes. Although the cost of replacing power converters is not as high as replacing a gearbox, their unpredicted failure can result in significant loss of production. CM of power converters is not straightforward and a number of sensors may need to be employed (including vibration, temperature, current and other sensors) in order to obtain useful information which can be used to determine the likelihood of an incipient failure.

So far CM of power converters has not been widespread at commercial level and is limited to very specific parametric measurements of limited diagnostic value as they cannot be used to predict a fault. Instead they are usually sufficient to diagnose the presence of a fault.

Wind farm operators may employ a corrective or proactive maintenance strategy. The main differences between the two strategies are as follows. In corrective maintenance a fault must be present before maintenance is carried out. Relevant resources may be kept in hand to speed up corrective maintenance activities or be put in place after a fault presents itself.

The latter case will probably result in excessive downtimes up to several months in the case of a gearbox failure. In proactive maintenance strategy the key consideration is the prevention of failure of a component. In order to achieve this, preventive or prognostic maintenance methods can be used.

Preventive maintenance is largely based on punctual diagnosis of the initiation of a fault. Prognostic maintenance on the other hand makes use of the diagnostic information available in order to predict the rate of deterioration of a component and its remaining lifetime.

Prognostic maintenance can optimise maintenance planning and ensure the availability of necessary material, equipment and personnel resources at the best time. Also preventive and prognostic maintenance aim to minimise the extent of repairs to the absolutely required in order to arrest the evolution of further damage in the system and minimise downtime required to carry out maintenance activities.

It is reported that for offshore wind farms the O&M costs account for typically 23% of the project's total expenditure as summarised in Table 1 and Figure 2, or alternatively this may be expressed as accounting for between 25-30% of the cost of unit of energy produced [28-34].

For an equivalent onshore project, the O&M costs as a percentage cost of the energy is estimated to be between 5-10% [33]. The main reason for such a difference may be attributed to the impact of operating a wind turbine in the marine environment where the wind turbines are 'stressed' in a harsher maritime environment and their accessibility for maintenance restricted by weather and sea-state conditions, and also by their distance to shore which affects accessibility, meaning maintenance expedition to offshore wind turbines tend to be more costly than visits to onshore wind turbines.

Table 1: Major cost components of an offshore wind farm [32]. The installation and decommissioning for the Opti-Owecs project has been included in the other subcategories, excluding the O&M.

Table 1: Major cost components of an offshore wind farm [32]. The installation and decommissioning for the Opti-Owecs project has been included in the other subcategories, excluding the O&M [6].

Component	% of energy cost (Opti-Owecs)	% of installed cost (Owecop)
Turbines and tower	34	25
Sub-structure and foundation	24	11
O&M	23	17
Electrical interconnection	15	17
Installation and decommissioning	included above	18
Other	4	12

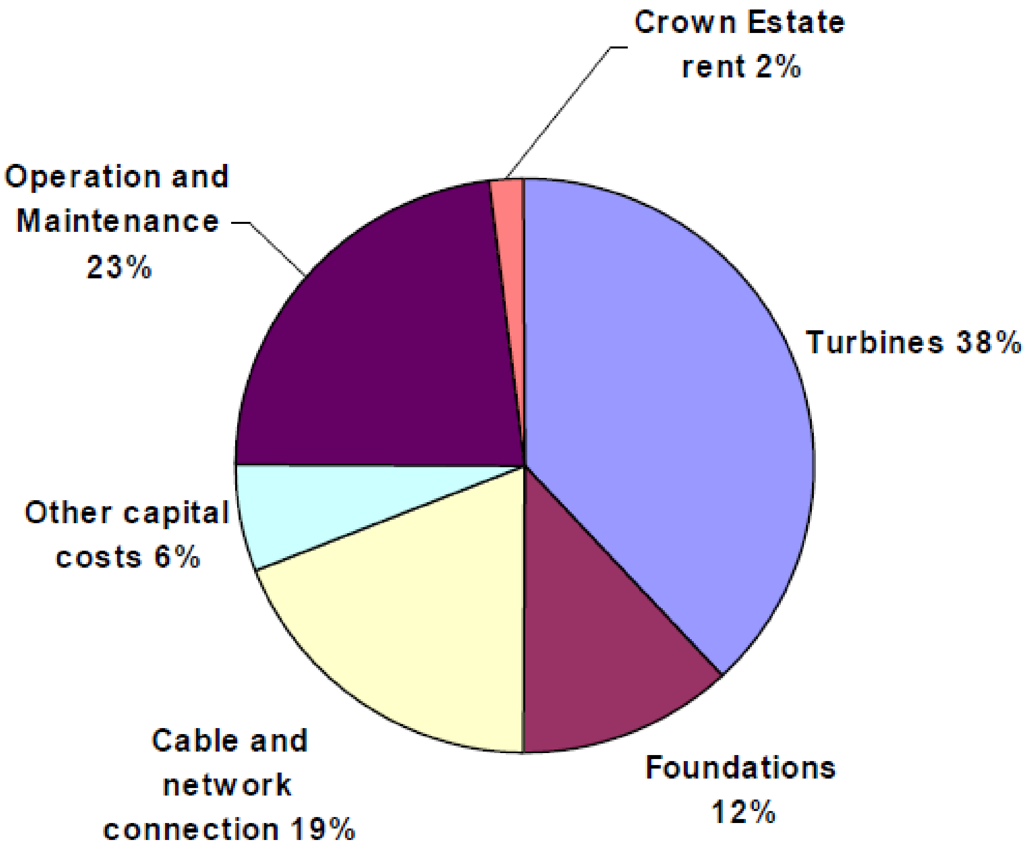

Figure 2: Average offshore wind farm cost breakdown in the UK [6].

2. Overview of wind turbine condition monitoring

CM systems currently employed by the wind energy industry are primarily based on vibration analysis, process parameter analysis and oil temperature measurements for the evaluation of the gearbox and generator. Intense research activity is currently on-going in the field of:

- Acoustic emission and vibration analysis for gearbox and generator CM
- Structural health monitoring of critical components such as the rotor, tower and foundation using various techniques including vibration analysis, acoustic emission detection, strain gauge measurements, long-range ultrasonics, automated scanners, thermography, radiography and eddy current testing.
- Thermographic analysis for inspection of electrical components
- Current and pressure sensing of electric motors and hydraulics respectively
- Oil analysis including wear particle type and dimension measurements and moisture measurements
- Time and frequency domain analysis of the electrical power
- Trending of key component response function
- Visual and acoustic examination to enhance maintenance planning
- Radar based measurements of structural components
- Data integration

Significant research effort has been allocated in the signal analysis methodology of the data acquired particularly in association with vibration, acoustic emission and oil analysis techniques. The purpose of this research is to increase the life of wind turbines through the accurate evaluation of the condition of wind turbine critical components and also to improve the maintenance planning. The improvement of maintenance scheduling and minimisation of unpredicted and corrective maintenance is at the moment the main purpose of the ongoing research. The wind energy industry hopes that ongoing development of the aforementioned CM techniques will not only allow early indication of incipient faults and failures but also permit an evolution from corrective to preventive and ultimately prognostic maintenance resulting in a significant increase in wind turbine availability and reliability.

The thorough analysis of data acquired by the Supervisory Control and Data Acquisition (SCADA) system is a key issue for researchers which can lead to a significant drop in the need to send maintenance engineers to carry out inspection activities on site. The integration of various CM techniques is also a profound element in the current research activities supported by the wind energy industry in achieving substantially improved wind turbine operational health management.

Although online predictive maintenance of wind turbine rotating components has evolved further based mainly on trending of vibration signatures and resulting spectra or other spectrum-based transforms it still remains unreliable and incorporates a high degree of uncertainty. Vibration data are acquired on a routine basis in larger industrial wind turbines and several commercial systems are available, which in certain cases even offer automated evaluation of rotating machinery. However, these expert systems require an extended amount of data since normal condition should be first well defined (trended) for each machine. Then any deviations on the characteristics of the acquired data arising due to developing faults will give indication of their presence.

This is a time consuming procedure since on each measurement location per component three directional vibration readings are required, as well as approximately six such readings for averaging in order to build the reference signature per direction and per location. This form of analysis in many cases can involve large errors in the diagnosis since structural vibration and background noise could alter the vibration profile and thus lead to a wrong evaluation of the actual condition of the machinery being inspected. Moreover, in most cases bearing faults remain difficult to diagnose and require further and more complex analysis which in many cases may not achieve the desirable result.

The application of Acoustic Emission (AE) for monitoring rotating machinery has been discussed in detail by several authors (Sato et al, Kerkyras, Douglas et al, Ghamdi et al). Non-commercial AE transducers have been used for monitoring purposes of rotating machinery to overcome the disadvantage of crystal ringing of AE piezoelectric transducers (PZT).

Crystal ringing causes PZT sensors to produce mainly their own resonances in the frequency domain and thus the interpretation of the resulting spectra is not reliable. Furthermore, accelerometers maintain a flat frequency response on white noise excitation but since they operate at lower frequencies in most cases these mask the diagnostic characteristics of the spectrum. An overview of studies on AE application on machine diagnosis has been recently presented by Mba et al. [35] Unfortunately, the aforementioned studies lack the verification data provided by a database based on extensive field trials and most rely on results produced using artificially induced faults, rather than defects which developed due to natural wear, improper installation or design restrictions.

There is a profound need to carry out trials in the field. This gap in the development of the condition monitoring technology for wind turbines was filled and demonstrated extensively by the consortium members involved in the NIMO FP7 project (www.nimoproject.eu). The project developed an integrated CM system which combined various sub-modules for the continuous evaluation of the gearbox, hydraulics, electric motors, blades and tower of the WT.

The only other instance where similar extensive work was carried out but focused on the CM of gearbox only was during the CONMOW project (FP6) whose results although where beneficial, did not really progress the condition monitoring technology for WT to the desired level. Some development work on gearbox CM took place during the INTELWIND FP7 project (www.intelwind-project.com) which focused on the development of an integrated CM system based on the combination of AE, vibration, torque and oil analysis sensors. The INTELWIND system was demonstrated on a wind turbine at the Lavreotiki wind farm owned by the Centre of Renewable Energy Sources and Saving in Greece.

As part of funded research through Regional Growth Fund, TWI worked on the development of Structural Health Monitoring (SHM) system that will enable the detection of faults and failures within wind turbine towers and blades. The system is based upon Acoustic Emission (AE) and Operational Modal Analysis (OMA) of wind turbine blades to detect the formation and propagation of cracks through both acoustic stress signals and changes in modal frequency. The system will also monitor stuctures such as the turbine tower and drive-train elements with acoustic emissions. The SHM system was tested on a blade at NAREC. Successful testing of the AE system on drive-train components has already been undertaken at TWI Cambridge on a WindMaster 300 Wind Turbine nacelle.

Research at the University of Oxford has focussed on the development of a gearbox condition monitoring system utilising eddy current sensors to detect wear and fatigue in WT gears. Bench tests have been undertaken on a simple gear-gear test rig, to determine the changes in sensor readings by comparing a gear with machined “defects” to a baseline of a gear with no defects. Various sensor installation methods were tested for detecting the known defects, each with varying successes. Typical failure modes included gear tooth root damage, face damage, surface galling and gear misalignments. Further research is required into the most appropriate solution for monitoring a whole gearbox, including an option for retrofitting an existing gearbox with minimal intrusion.

Research at UoB funded by EMRS DTC and EPSRC has developed a single-sensor solution to monitor wind turbine vibration, blade damage and ice build-up. The system is based upon the use of navigation satellites (GPS or similar) and a receive-only RF sensor that is fixed externally to the turbine. By monitoring the satellite signals that reflect off the wind turbine, the structural status of the wind turbine can be inferred. The sensor equipment required is very low cost as it is used in GPS chips for navigation and is therefore in mass-production already. A further benefit of the system would be the installation procedure; the sensor can be externally mounted to the turbine tower without the need for temporarily stopping the turbine.

Testing has already been successfully undertaken on helicopter blades, accurately detecting both blade passing frequency and helicopter body vibration frequencies. Radar experiments have been undertaken with scaled wind turbine models in an anechoic chamber to understand the signal phenomenology of different structural faults. Currently, the system is being tested on a 90m diameter wind turbine in Garstang, Lancashire.

3. Current state-of-the art in wind turbine condition monitoring

Machinery condition monitoring is defined as the process of monitoring a parameter of condition in machinery such that a significant change is indicative of a developing failure. Thanks to condition monitoring it is possible to prevent early breakdown, reduce the number of inspections, improve the capacity factor, built wind farms in remote places and improve maintenance scheduling.

There are two main types of condition monitoring concepts. These are a) online which involves continuous monitoring of the nacelle components concerned and b) offline which involves only periodic monitoring. However, it should be noted here that in certain cases on-line continuous monitoring can be carried out at intervals because in certain cases there is no need to monitor certain subcomponents continuously. Therefore a more appropriate definition for online condition monitoring could be when the sensors used for monitoring a specific component are permanently installed for this purpose [14].

Online condition monitoring involves the continuous or scheduled acquisition of data while offline condition monitoring involves data acquisition during a specific period during which a component is under evaluation. Although offline condition monitoring is not ideal, it can be sufficient for the evaluation of onshore wind turbines. However, this is not the case for offshore wind farms where accessibility is not straightforward and in certain cases adverse weather conditions may postpone the visit of maintenance engineers to carry out scheduled inspection on the turbines for extended periods of time which can range from a few days up to a few weeks [14]. Consequently, although offline monitoring is standard practice on commercial wind turbines, modern designs need to consider online condition monitoring systems which offer several advantages over offline systems.

The main advantages of online condition monitoring systems are the fact that they offer the possibility of early warning thus limiting the likelihood of unpredicted failures and downtime. Furthermore they enable better planning of maintenance schedules and under certain conditions they can be used to identify the exact problem remotely allowing the right service at the right time, minimizing unnecessary replacements and related costs.

There are different methods on which monitoring systems are based on. They are accounted below [14]:

- Vibration analysis.

Currently the most extensive technology applied for condition monitoring, especially for rotating equipment. In the case of wind turbines it has been applied for gearbox, generator bearing and main bearing CM. Generally, a baseline sample of vibration levels is collected for a healthy wind turbine, from which operating vibrations are compared. An “out of range” vibration will signify a fault, which can be further diagnosed by analysing the frequency of the vibration.

- Acoustic Emission.

AE is related to vibration monitoring but with a different principle because in the acoustic monitoring case, the acoustic sensors “listen” to the component instead of registering its local motion. AE sensors detect the stress waves that are generated during crack initiation and propagation within materials. AE has been shown to detect some faults earlier than vibration analysis. AE has been applied successfully to gearboxes, bearings and blades. The AE technique does not require trending like the vibration method. Although at the moment AE has found limited use so far in the wind energy industry largely due to the lack of sufficient experience with the application of this technique for WT gearbox monitoring this will change in the near future. The first significant step towards this direction was made during the NIMO project.

- Oil analysis.

Oil analysis is mainly carried out offline by taking oil samples for laboratory evaluation. However for safeguarding the oil quality, application of on-line sensors is increasing since various oil analysis sensors are nowadays available at an acceptable price including wear debris detectors and moisture sensors which measure the presence of water in the lubricant oil of the WT gearbox. Characterisation of parts is often only performed in case of abnormalities. Practically all utility scale WTs employ oil temperature sensors nowadays to avoid overheating of the lubricating oil which may result in combustion and subsequently loss of a WT due to fire.

- Thermography

Thermography is often used for monitoring electrical and electronic components; in particular it could be applied to monitor failure prone power electronics. Currently, this technique is only applied off-line, but the development of on-line monitoring techniques will likely induce a larger uptake in this technology for turbine monitoring.

- Strain measurement.

Strain measurement of turbine blades is generally performed with strain gauges, however the development of a cost effective optical fibre strain measurement device will likely increase the use of strain measurements for turbine monitoring.

- Ultrasonic.

Widely used for the analysis of turbine towers and blades, ultrasonic techniques can evaluate the structural integrity of the turbine by detailing the size and location of defects within the material.

- Eddy current inspection.

Eddy current sensors are a well-established technology that are commonly used within NDT technology. By utilising either a permanent or oscillating magnetic field, the passing of conducting material induces eddy currents into the material. This in turn generates an opposing magnetic field, which leads to a change in voltage within the sensing coil. Eddy current inspection can be applied for the detection of fatigue cracks on the WT tower. However, encircling coils have been lately applied for detection of debris in the lubricant as mentioned earlier in this section. Any metallic debris ferrous or non-ferrous passing through the encircling coil will change its impedance response. Depending on the amount and type of change in the impedance response of the encircling coil the nature of the particle, ferrous or non-ferrous that caused the variation in the electromagnetic field within the sensor can be ascertained together with its dimensional range.

- Radiography.

Taking X-rays of blades and towers is very rarely undertaken in the wind industry, although it can provide useful information regarding the structural condition of the turbine. Portable radiography based systems will reduce the cost of this technique which may increase its use within industry.

- Shock Pulse Method

Only occasionally used within industry, the shock pulse method detects shock waves when a rolling element in a bearing comes into contact with a damaged area of the raceway or debris.

- Electrical Effects.

Motor Current Signature Analysis or MCSA is used to detect unusual phenomena in electrical components.

- Process parameters.

The evaluation of process parameters is a very common practice in order to evaluate the overall operation condition of wind turbines. The control system of the turbine becomes more sophisticated and the diagnostic capabilities improve.

- Performance monitoring.

For security and improved performance purposes, the relationship between wind speed, power, blade angle and rotor speed can be used to evaluate the condition of the wind turbine. In the event of large deviations an alarm is generated.

An overview describing the different type of faults associated with the nacelle components is given below.

- Gearbox and bearing defects.

Gear and bearing faults are both common with bearing failure being the leading factor of turbine gearbox failure. The parts that are more likely to fail are the planet bearings, the intermediate shaft-locating bearings and high-speed locating bearings, while the planet carrier bearings, hollow shaft bearings and non-locating bearings are most unlikely to fail. Misalignment problems is also a relatively common problem in WT gearboxes which can result in poor contact angles between the gear teeth increasing the stresses sustained and causing early fatigue failure. Furthermore, misalignment can contribute to bearing related problems.

Currently vibration measurement and spectrum analysis are typical choices for gearbox monitoring and diagnostics. Also manual-based oil analysis can be used to assess the condition of the bearings based on particle counting.

- Generators.

Generator bearing faults and stator insulation breakdown (which form up the generator) are the main causes of generator failures. Faults in induction generators produce one or more of the following symptoms: unbalanced air-gap voltages and line currents, increased torque pulsation, decreased average torque, increased losses and reduction in efficiency, disturbances in the current, voltage and flux waveforms.

Motor current signature analysis (MCSA) has been investigated for turn-to-turn faults based on generator current spectrum analysis.

- Power electronics and Electric Controls.

Electronic controls account for only about 1% of the cost of a wind turbine, but cause 13% of failures. Thermography is often applied for monitoring and failure identification of electronic and electric components. Hot spots, due to degeneration of components or bad contact can be identified in a simple and fast manner. The technique is only applied for off line usage and interpretation of the results is always visual. At this moment the technique is not interesting for on-line condition monitoring.

- Yaw System.

The change in degrees of yaw gives the degree of fault like 5° (within normal operating range), 10° (unusual wind changes), and 20° (significant loads on wings). The analysis of the yaw error simulations showed that the level at the 1P-frequency of the electrical power is altered by the amount of yaw error which makes it possible to distinguish between rotor blade pitch errors and rotor yaw errors, since only the latter has influence on the 1P-level frequency.

- Pitch Mechanism.

Problems in the pitch bearing are currently of concern to WT manufacturers and operators. However, due to the very limited motion of the pitch mechanism (approximately 90°) conventional vibration analysis is not applicable. AE is also unlikely to prove successful due to the amount of the limiting motion in detecting faults in pitch bearing. Measurements related to the motor of the pitch mechanism may provide more useful information regarding the overall condition. Nonetheless, simulations have shown that pitch error is detectable by the 1P-amplitude of the acceleration in the X and Z direction, where a difference of 3–4 dB between pitch error increments of 0.5° is observed.

4. Condition monitoring of wind turbine gearbox and other nacelle components

Table 2 summarises the typical nacelle defects commonly detected by wind turbine operators as well as the techniques used to evaluate them. Apart from condition monitoring, visual inspection of certain components is also carried out periodically. With the evolution of condition monitoring systems visual inspection will probably be virtually phased out completely in the forthcoming years.

Table 2: Typical gearbox and other nacelle component defects and common inspection/condition monitoring techniques employed by the wind energy industry for their detection and evaluation. A: Severity in case of occurrence (1=lowest, 5=highest), B: Interest in improving detection by the wind energy industry (1=lowest, 5=highest).

NACELLE DEFECTS, FAULTS, FAILURES	CURRENT INSPECTION	A	B
1. Main Bearings	Every 12 months, vibration analysis.	5	5
2. Gearbox			
Housing cracks	Every 6 monhs, standard preventive inspections.	5	3
Bearings	Every 6 months, standard preventive inspections (sound and/or debris). Videoscope inspections. Not scheduled. Every 12 months, vibration analysis.	4	5
Gears (Pitting, spalling, scuffing, cracks, corrosion...)	Every 6 months, standard preventive inspections (visual and/or debris). Videoscope inspections. Not scheduled. Every 12 months, vibration analysis.	5	5
Lubricant	Every 6 months, oil analysis	4	5
3. Coupling			
Misalignment	Every 12 months, vibration analysis. Alignment every 24 months.	3	5
4. Generator			
Bearings	Every 6 months, standard preventive inspection (sound) and global vibration measurement. Every 12 months, vibration analysis.	4	5
Unbalance	Every 12 months, vibration analysis	3	3
Other damages	Every 12 months, vibration analysis	3	5
5. Yaw System			
Yaw drive	Every 6 months, standard preventive inspections	2	4
Yaw gear	Every 6 months, standard preventive inspections	5	3
Yaw bearings		5	3
6. Blades bearings		5	5
7. Hydraulic Unit	Every 6 months, standard preventive inspections and oil analysis. Pressure sensors.	4	5

5. Condition monitoring of wind turbine power electronics

Condition monitoring of power electronic converters is still in the early stages of development and faces a lot of challenges as power electronic converters are complex systems with many components. Semiconductor devices and capacitors have been identified as the main sources of power electronics converter failure, thus condition monitoring is focused predominantly on those components. Semiconductor degradation is most often caused by packaging fatigue due to the different coefficients of thermal expansion (CTEs) of the materials used. It causes the chip temperature to rise above the maximum operating level and leads to device failure. In electrolytic capacitors degradation is manifested through their increased equivalent series resistance. The challenge faced by power electronics condition monitoring is that the parameters indicative of device degradation, such as the chip junction temperature, are very difficult to measure during operation [36-37].

In principle condition monitoring of power electronics can be implemented by:

a) measuring parameters indicative of fatigue development such as on-state voltage and resistance, threshold gate voltage and thermal resistance,
b) embedded sensors such as mechanical strain gauges or the use of dummy chips that can register directly the bonding material's fatigue, or
c) developing a model for the converter's healthy condition and a logic which can detect degradation by repeatedly comparing the system's real-time response to the model.

Various research attempts to monitor power electronics can be divided into the following categories:

1. On-State Voltage (Vce) or Resistance (Ron) Based CM for Bond Wire Liftoff Detection.
   The multiple thin wires connecting the chip emitter to the Direct Bonded Copper (DBC) plate of a standard IGBT power module are one of the elements most susceptible to creep fatigue damage. The gradual peeling off of the wire heel from the emitter is detectable through increased resistance and change of the chip on-state voltage as the path of current flow is being restricted. Despite its simplicity, this CM method is rather difficult to achieve for real time measurements with guaranteed accuracy because of the relatively small value of the ON-state voltage on the background of the dramatic switching transient and the changes due to different current levels. The physical dimension, isolation, cost and integration of the sensing circuits within the power module also pose difficulties for the practical implementation of this system. The ON-state voltage measurement has been applied as quasi real-time failure prognostic method in an electric vehicle application where the on-state voltage was measured only at cold start-up with known starting current.

   Recent research also suggests that monitoring using the rate of change rather than the actual measurement of the ON-state voltage, i.e. dVce/dt, may prove to be easier to achieve.

2. *Thermal Resistance and Temperature-Based CM.*
   In standard power modules the bottom side of the semiconductor die (e.g. the IGBT collector) is soldered on to the DBC plate providing electrical insulation, but

conduction for the heat generated during power cycling which if not expelled will damage the chip. The different CTEs of the material layers involved cause them to expand and contract differently with respect to one another, which usually results in cracks and voids spreading though the solder bond holding them together. This obstructs heat transfer and eventually leads to chip failure. A few monitoring techniques (e.g. based on Vce measurements at very low currents, the decrease of threshold gate voltage Vge, etc.) have been tested and proved in laboratory conditions, but found unsuitable for real time condition monitoring systems. A technique based on the dIc/dt and dVge/dt used to derive the transconductance of the IGBT which is a thermosensistive parameter has also been suggested as more suitable for on-line application. But it was found to be affected by noise and by the presence of temperature compensated gate resistors used in some IGBTs. Another promising direction of research is to use converter terminal voltage and current and external case temperature to derive the junction temperature T_j. Power losses are estimated real time and used to derive the junction temperature from compact thermal models. Combined with cycle counting methods, this can provide a reasonable indication of the converter health. The difficulty with temperature based CM methods is that the error for estimation of T_j needs to be limited within 1° C because the maximum rise of T_j due to solder fatigue is about 10°C. It is rather difficult to achieve that based on external temperature measurements under the masking effects of the converter variable operating point and the effects from other mechanisms of degradation such as bond wire liftoff.

3. Switch-Time-Based CM for the Power Device and its Gate Driver.
   Another parameter which can be used to signify the presence of several failure mechanisms is the increase of the switching time. The advantage of this method is that it uses the gate driver signals of each individual device and thus offers noise immune means of monitoring PE systems. It has been applied in GTO systems (which have long switching times of the order of 10μs). However for MOSFET or IGBT converters where the switching time is in the range of 100-500 ns, this method is still not deemed practical. This method however may further be developed using indirect techniques of switch-time measurements such as the high frequency electromagnetic interference signal change.

4. Gate-Signal-Based CM for Gate Degradation.
   A method based on the waveform of the gate voltage during turn ON is suggested for detecting short circuit IGBT faults. Experiments indicate there is a marked difference in the level and duration of the Miller gate plateau in the case of the healthy and the faulty devices. This method is not yet developed for condition monitoring systems; the limitation being that very high sampling resolution is necessary for the measurements to capture and plot the Miller Plateau, therefore other ways are considered such as using analogue electronics to obtain cumulative charge signature which can be applicable for monitoring of converters where immediate shut-down is not necessary.

5. In-situ or Sensor-Based CM.
   The IGBT module manufacturer Semikron presented a method for CM using sensor integrated in the DBC of the module to monitor the change of resistance resulting from wire bond liftoff. More recently Fraunhofer reported a condition monitoring system using in-situ life cycle logic units (LCU) with sensors directly measuring

parameters such as the chip temperature, etc. and using rainflow analysis to make predictions about the unit's remaining lifetime; these methods are reported to have produced accurate results. However, they necessitate direct access to the chip and changes of the power module design. As such, they are open only to device manufactures to start producing condition monitoring enabled semiconductor modules, and not for monitoring of wider range of power electronics devices currently in operation and on the market.

6. System-Identification-Based CM.
   As the degradation of a power device usually affects the converter as a whole and in theory changes identified on system level can be used for condition monitoring as well. For example, monitoring technique for the health condition of output filter capacitors has been reported using the shift of frequency response. Potentially other parametric variations available on system level can be used to provide early warning for developing faults. Development of neural networks may provide the answer to power electronics condition monitoring. Such a network has been applied to a diode rectifier and was able to detect most relevant component changes. System based condition monitoring for power electronics is still underdeveloped though, and is dependant upon factors like establishing unambiguous correlations between specific failure modes and the system response, advanced processing algorithms and increased demand on the computing hardware and attenuation of high frequency noise.

The advantages and disadvantages of the means of condition monitoring for power electronics explored so far is summarised below in Table 3.

Table 3: Advantages and disadvantages of condition monitoring method for power electronics.

CM Method	**Advantages**	**Disadvantages**
Vce, Ron	High relevance for detection of degradation	Difficult to measure small variations of Vce signal
Rth (thermal resistance)	Identifying solder fatigue	Difficult to measure Tj
Gate voltage waveform	Identifying electrical faults	High real-time requirement
Prolonged switch-time	Identifying gate drive failures	Hard to measure ns-range switching times
Embedded sensors	Reliable and accurate	DBC modification is necessary; expensive CM
System-level identification	No additional hardware required	Difficult to correlated faults with system symptoms; complicated algorithms neede

Condition monitoring for power electronics is still in its embryonic stages, but there is increased interest for developing it especially for applications where not only increased design reliability, but also visibility over the system's operation is necessary for remote control and protection. Regardless of how much the design time of a system is increased through novel device design and redundancy, occasional faults may still occur and remote monitoring still remains the only way to get early warning and prevent catastrophic failure.

6. Condition monitoring requirements for wind turbines

To effectively monitor all components within a wind turbine using conventional CM tactics it is conceivable that the requirements stated in Table 4 are required. This data illustrates the amount of data that would typically be collected per day for monitoring a single wind turbine.

Table 4: Typical wind turbine monitoring requirements.

Location	Measurement	Sample Rate (Sa/s)	Quantity
Blade 1	Load (X&Y)	1000	2
Blade 2	Load (X&Y)	1000	2
Blade 3	Load (X&Y)	1000	2
Main Bearing	Vibration (X&Y&Z)	2000	6
Main Bearing	Temperature	1	4
Gearbox LSS Bearing	Vibration (X&Y&Z)	2000	3
Gearbox LSS Bearing	Temperature	1	4
Low Speed Shaft	Torque	1000	1
GB Stage 3	Vibration (X&Y)	2000	2
GB Stage 3	Temperature	1	4
GB Stage 2	Vibration (X&Y)	2000	2
GB Stage 2	Temperature	1	4
GB Stage 1	Vibration (X&Y)	2000	2
GB Stage 1	Temperature	1	4
Gearbox HSS Bearing	Vibration (X&Y&Z)	2000	3
Gearbox HSS Bearing	Temperature	1	4
Gen DE Bearing	Vibration (X&Y)	2000	2
Gen DE Bearing	Temperature	1	4
Gen NDE Bearing	Vibration (X&Y)	2000	2
Gen NDE Bearing	Temperature	1	4
Gen Windings	Temperature	1	12
Encoder	Shaft Speed	10	1
Tower	X,Y,Z Sway	1000	3
Converter	Voltage	25600	3
Converter	Current	25600	3
Total samples		207654	
Total data per day (32 bit storage)		72 GB per day	

Clearly, transferring 72GB of data daily per turbine would be inefficient for turbine monitoring as it would add significantly to the technical complexity of any system, and therefore increasing system cost. For this reason, many systems have adopted on-site analysis of data and transfer only a reduced amount of raw or aggregated data.

Furthermore, Key Parameter Indicators (KPIs) can be established for certain components being monitored. In the event where the value of one or more KPIs exceed a certain threshold an alarm can be given and the signal which provided the alarm can be downloaded assessed further.

Certain commercial systems such as the Bruel and Kjaer's Vibro system (2) transfer high resolution data once readings have passed a pre-defined threshold, which can then be monitored at a central data analysis centre. Another method of reducing data transfer requirements includes Gram and Juhl's Turbine Condition Monitoring (TCM) system (10). This system uses multiple sensors that feed into an on-site processing unit on the turbine. It is then the results of the analysis that are reported back to the wind farm server system, rather than the raw data.

With the high rates of data transfer associated with the full analysis of a wind turbine as suggested in Table 4, it has been suggested that a more efficient method of monitoring a turbine would be to closely monitor only the most critical/failure prone components within the turbine. This is the main driver for OPTIMUS's focus on condition monitoring of drive-train and power electronic components.

7. Commercially available condition monitoring systems

There are several wind turbine condition monitoring systems which are commercial today. Several of the available commercial wind turbine condition monitoring systems have been certified by Germanischer Lloyd or other certification organisations. Manufacturers of wind turbine condition monitoring systems can be found from all over the world with a significant number of them based in Europe.

The list of available commercial wind turbine condition monitoring products is constantly growing with more organisations trying to enter the market. There is a particular interest from SMEs in entering the wind turbine condition monitoring market which is currently dominated by larger industrial organisations.

The WT CM market is particularly competitive and CMS cost remains a key factor during selection. In the future other factors including stricter insurance company requirements will play a significant role in the selection of CMS and components being monitored.

Practically all industrial wind turbines make use of some sort of CMS which in most cases includes vibration analysis capability apart from temperature measurements. Depending n the system used and the available signal analysis methodologies the reliability of the resulting information gained from the CMS can vary significantly. Sampling rates, types of sensors number of sensors used and signal processing methodologies may differ substantially for CMS provided by different manufacturers.

It is important to minimise the number of sensors required to monitor critical components such as the gearbox, generator, main bearing or power electronics in order to keep the cost of the CMS as low as possible. An acceptable CMS cost cannot exceed €10,000-15,000 for most large scale commercial WTs under the current status quo. In certain cases operators may opt for manual measurements rather than continuous monitoring.

It is important to acknowledge the effect of variable wind speed and wind turbulence during vibration, AE and oil analysis measurements related to the gearbox and generator. The value, efficiency and reliability of CMS is yet to be proven due to the very unpredictable and variable loading conditions under which WTs operate.

However, insurance policies do require by default the use of CMS and therefore operators and manufacturers have no other option than to use such systems. However, in the future insurance requirements will become stricter and the exact output of CMS will be taken into account whenever claims are filed. Also operators will probably become more interested in verifying the exact condition of WTs that pass to their responsibility after the guarantee from the manufacturer has ended.

Previous research efforts (Crabtree C. J., 2010), (Tavner, 2012) have identified commercially available condition monitoring systems, which have been analysed in terms of the monitoring technology and analysis methods. This previous work is detailed in Table 5 and has been expanded upon with more up-to-date sources.

Table 5: Details of commercially available CM systems

Product and Company Information[+] — Product Details (based on available literature and contact with industry including EWEC 2008,2009,2010,2011,2012)[+]

Ref.	Product	Supplier (Known Users)	Country of origin	Description	Main components monitored	Monitoring technology	Analysis methods	Data rate or sampling frequency	Other comments
1[*+]	Ascent	Commtest	New Zealand	System available in 3 complexity levels. Level 3 includes frequency band alarms, machine template creation, statistical alarming.	Main shaft, gearbox, generator	Vibration (accelerometer)	FFT frequency domain analysis Envelope analysis Time domain analysis	-	
2[*+]	Bruel & Kjaer Vibro	Bruel & Kjaer (Vestas)	Denmark	Vibration and process data automatically monitored at fixed intervals and remotely sent to the diagnostic server. User-requested time waveforms for frequency and time series analysis Time waveform automatically stored before and after user-defined event allowing advanced vibration post-analysis to identify developing faults.	Main bearing, gearbox, generator, nacelle. Nacelle temperature. Noise in the nacelle.	Vibration analysis Temperature sensor Acoustic	Time domain FFT frequency analysis	Variable up to 40kHz 25.6kHz	
3[*+]	CMS	Nordex	Germany	Start-up period acquires vibration 'fingerprint' components. Actual values automatically compared by frequency, envelope and order analysis, with the reference values stored in the system. Some Nordex turbines also use the Moog Insensys fibre optic measurement system.	Main bearing, gearbox, generator	Vibration analysis (accelerometer)	Time domain based on initial 'fingerprint'	-	
4[*+]	Condition Based Maintenance System (CBM)	GE (Bently Nevada)	USA	This is built upon the Bentley Nevada ADAPT.wind technology and System 1. Basis on System 1 gives monitoring and diagnostics of drive train parameters such as vibration and temperature. Correlate machine	Main bearing, gearbox, generator, nacelle. Optional bearing and oil	Vibration analysis (accelerometer)	FFT frequency domain analysis Acceleration enveloping	-	

				information with operational information such as machine speed, electrical load and wind speed. Alarms are sent via the SCADA network.	temperature.				
5*+	Condition Diagnostics System	Winergy	Germany	Up to 6 inputs per module. The system analyses vibration levels, load and oil to give diagnostics, forecasts and recommendations for corrective action. Automatic fault identification is provided. Relevant information provided in an automated format to the operations and maintenance centre without any experts being involved. Information delivered to the appropriate parties in real time. Pitch, controller, yaw and inverter monitoring can also be included.	Main shaft, gearbox, generator	Vibration (accelerometer) Oil debris particle counter	Time domain FFT frequency domain analysis	96kHz per channel	
6*+	Condition Management System	Moventas	Finland	Compact system measuring temperature, vibration, load, pressure, speed, oil aging and oil particle count. 16 analogue channels can be extended with adapter. Data accessed remotely via TCP/IP. Mobile interface available.	Gearbox, generator, rotor, turbine controller	Vibration Oil quality/particles Torque Temperature	Time domain (Possible FFT)	-	
7*+	OneProd Wind	Areva (01dB-Metravib)	France	Eight to 32 channels. Instrumentation includes operating condition channels to trigger data acquisitions, measurement channels for surveillance and diagnosis. Data set comparison when relating to similar operating conditions; data alarm systems warn on the repetitive and abnormal shocks enabling the detection of failure modes; built-in diagnostic tool. Optional additional sensors for shaft displacement, for permanent oil quality monitoring, low frequency sensors on the structure and current and voltage	Main bearing on LSS Bearing on gearbox LSS Bearing on intermediate gearbox shaft, on gearbox high-speed shaft, on generator Oil debris, structure, shaft displacement, electrical signals.	Vibration Electrical signature analysis Thermography Oil debris particle counter	Time domain FFT frequency analysis	-	

				sensors for generator monitoring.					
8*+	SMP-8C	Gamesa Eolica	Spain	Continuous on-line vibration measurement of main shaft, gearbox and generator. Comparison of spectra trends. Warnings and alarm transmission connected to Wind Farm Management System.	Main shaft, gearbox, generator	Vibration analysis	FFT frequency domain	-	
9*+	Ω Guard CMS	Bachmann	Austria	Vibration based system based on KPI measurements	Gearbox, tower and pitch	Vibration analysis	Signal envelope, RMS and peak-peak	25kHz gearbox, 250 Hz tower	Six accelerometers with operational range of 0.1 Hz–10 kHz for gearbox, one acceleration sensor each in the axial direction (wind direction), as well at right angles to it with a frequency range of 0.1 Hz–100 Hz for tower
10*+	TCM (Turbine Condition Monitoring)	*+Gram & Juhl A/S (Siemens Wind Power A/S) +Enterprise V6 Solution with SCADA Integration	Denmark	Advanced signal analysis and process signals combined with automation rules for algorithms for generating references and alarms. M-System hardware features up to 12/24 synchronous channels, interface for structural vibration monitoring and RPM sensors, external process parameters and analogur outputs. TCM server stores data and does the post data processing. Control room with web based operator interface.	Tower, blades, shaft and nacelle Main bearing, gearbox and generator	Vibration (accelerometer) Sound analysis Strain analysis Process signals analysis	FFT and Wavelet frequency domain analysis Envelope analysis RMS analysis Order tracking analysis		
11*+	WindCon 3.0	SKF (REPower)	Sweden	Lubrication, blade and gearbox oil systems can be remotely monitored through SKF ProCon software. WindCon 3.0 collects, analyses and compiles operating data that can be configured to suit management,	Blade, main bearing, shaft, gearbox, generator, tower, generator electrical	Vibration (accelerometer, proximity probe) Oil debris particle counter	FFT frequency domain analysis Envelope analysis Time domain	Analogue: DC to 40kHz (Variable, channel dependent) Digital:	

				operators or maintenance engineers.			analysis	0.1Hz – 20kHz	
12	WinTControl-1	Flender Service GmbH	Germany	Integrated system combining various sensors for continuous measurements	Nacelle, pitch mechanism, gear unit	Temperature and currents, nacelle vibration	Peak-peak, temperature values, current measurements	30Hz continuous	30 channels including vibration of nacelle in X and Y direction, air temperature, temperature and current of pitch motors, azimuth angle, wind speed, gear unit temperature
13*+	WinTControl -2	Flender Service GmbH	Germany	Vibration analysis system integrated with other sensors	Gearbox, generator and main bearing	Vibration analysis, parametric input (RPM, wind speed), temperature measurements	Peak-peak, FFT, signal envelope	Max 150kHz	17 channels vibration of main bearing, gearbox, generator, RPM, Phase position, generator performance, wind speed, main bearing temperature, gear unit temperature, generator temperature
14*+	WiPro	FAG Industrial Services GmbH	Germany	Measurement of vibration and other parameters given appropriate sensors. Time and frequency domain analysis carried out during alarm situations. Allows speed-dependent frequency band tracking and speed-variable alarm level.	Main bearing, shaft, gearbox, generator, temperature. (Adaptable inputs)	Vibration (accelerometer)	FFT frequency domain Time domain analysis	Variable up to 50kHz	
15*+	WP4086	Mita-Teknik	Denmark	Up to 8 accelerometers for real-time frequency and time domain analysis. Warnings/alarms set for both time and frequency domains based on predefined statistical/thresholds-based vibration limits. Operational parameters recorded alongside with vibration signals/spectra and full	Main bearing, gearbox, generator	Vibration (accelerometer)	FFT amplitude spectra FFT envelope spectra Time domain magnitude Comb filtering,	12-bit channel res Variable up to 10kHz	

				integration into gateway SCADA system. Algorithm toolbox for diagnostic analysis. Approximately 5000-8000 variables covering different production classes.			whitening, Kurtogram analysis		
16[*+]	HYDACLab	HYDAC Filtertechnik GmbH	Germany	Permanent monitoring system to monitor particles (including air bubbles) in hydraulic and lube oil systems.	Lubrication oil and cooling fluid quality	Oil debris particle counter	n/a	-	
17[*+]	PCM200	Pall Industrial Manufacturing (Pall Europe Ltd)	USA (UK)	Fluid cleanliness monitor reports test data in real-time so ongoing assessments can be made. Can be permanently installed or portable.	Lubrication oil cleanliness	Oil cleanliness sensor	n/a	-	
18[*+]	TechAlert 10 TechAlert 20	MACOM	UK	TechAlert 10 is an inductive sensor to count and size ferrous and non-ferrous debris in circulating oil systems. TechAlert 20 is a magnetic sensor to count ferrous particles.	Lubrication oil quality	Inductive or magnetic oil debris particle counter	n/a	-	
19[*+]	BLADEcontrol	IGUS ITS GmbH	Germany	Accelerometers are bonded directly to the blades and a hub measurement unit transfers data wirelessly to the nacelle. Blades are assessed by comparing spectra with those stored for common conditions. Measurement and analysis data are stored centrally and blade condition displayed using a web browser.	Blades	Accelerometer	FFT frequency domain	= 1kHz	Now part of Bosch Rexroth
20[*+]	FS2500	FiberSensing	Portugal	BraggSCOPE measurement unit designed for industrial environments to interrogate up to 4 Fiber Bragg Grating sensors. Acceleration, tilt, displacement, strain, temperature and pressure measurable.	Blades	Fibre optic	Unknown	Up to 2kHz	
21[*+]	RMS (Rotor Monitoring System)	Moog Insensys Ltd	UK	Modular blade sensing system consisting of 18 sensors, 6 per blade, installed in the cylindrical root section of each blade to provide	Blades	Fibre optic strain	Time domain strain analysis	25Hz/sensor	

				edgewise and flapwise bending moment data. Can be designed-in during turbine manufacture or retrofitted. Monitors turbine rotor performance, mass and aerodynamic imbalance, blade bending moments, icing, damage and lightning strikes. Possible integration, as an external input, in commercial available CMSs.					
22[+]	Adapt.wind	GE Energy	USA	Up to 150 static variables monitored and trended per WT. Planetary cumulative impulse detection algorithm to detect debris particles through the gearbox planetary stage. Dynamic energy index algorithm to spread the variation over five bands of operation for spectral energy calculations and earlier fault detection. Alarm, diagnostic, analytic and reporting capabilities facilitate maintenance with actionable recommendations. Possible integration with SCADA system.	Main bearing, gearbox, generator	Vibration (accelerometer) Oil debris particle counter	FFT frequency domain analysis Time domain analysis	-	
23[+]	APPA System	OrtoSense	Denmark	Oscillation technology based on interference analysis that replicates the human ear's ability to perceive sound.	Main bearing, gearbox and generator	Vibration	Auditory perceptual pulse analysis (APPA)	-	
24[+]	Distributed condition monitoring system	National Instruments	USA	Up to 32 channels; default configuration: 16 accelerometer/microphone, 4 proximity probe and 8 tachometer input channels. Also provided mixed-measurement capability for strain, temperature, acoustics, voltage, current and electrical power. Oil particulate counts and fibre optic sensing can also be added to the system. Possible integration into SCADA systems.	Main bearing, gearbox, generator	Vibration Acoustic	Spectral analysis Level measurements Order analysis Waterfall plots Order tracking Shaft centre-line measurements	24-bit res 23.04kHz of bandwidth with antialiasing filters per accelerometer/microphone channel	

							Bode plots		
25[+]	Wind AnalytiX	ICONICS	USA	This software solution uses fault detection and diagnostics technology that identifies equipment and energy inefficiencies and provides possible causes that help in predicting plant operations, resulting in reduced downtime and costs related to diagnostic and repair.	Main WT components	Vibration (accelerometer)			
26[+]	Wind Turbine In-Service	ABS Consulting	USA	Data gathered from inspections, vibration sensors and SCADA system. Ekho for WIND software features regular diagnostics, dynamic performance reports, key performance indicators, fleet-wide analysis, forecasts/schedules and asset benchmarking. It generates alarms and notifications or triggers work orders for inspections or repairs.	Main bearing, gearbox and generator Gearbox and gear oil, rotor blades and coatings	Vibration Inspections	FFT frequency domain analysis Time domain analysis		
27	Proficy Smart Signal	GE	USA	Based on Similarity Based Modelling (SBM).	Vibration and thermal analysis Critical rotating and non-rotating equipment	Software only, can conceivably compare signals from any existing instrumentation and compare results to a pre-defined threshold.			
28	Efector Octavis	IFM Electronic	Australia	Either on-site analysis or data transfer to server possible depending upon bandwidth of connection.	Generator, gearbox, rotor bearing. Can be extended to rotor blade and pumps/motors.	Vibration	Trend Recording FFT		Company develop sensors and have since developed a CM system for the wind industry.
29	Sensor Highway II	Mistras Group	USA	The Sensor Highway™ II (SHII) is an Acoustic Emission (AE) monitoring system with up to 16 high-speed		Acoustic Emissions	SHII-DC Basic and low cost system		Primarily developed for structures, in particular bridges

				channels and 16 standard parametric input channels (expandable to over 100). The system is designed for unattended and remote monitoring use in structural health, process and condition monitoring applications.			capable of data acquisition and storage with basic processing and alarm signals SHII-N Includes a built in Ethernet hub to connect multiple SHIIs to a base computer for analysis		
30	ConWind (Vibroweb XP)	Prüftechnik	Germany	Expert vibration analysis system	Main bearing, Gearbox, Generator, Nacelle	Vibration measured with piezo-electric accelerometers	Vibxpert (mobile CMS) 2 channel FFT data collection. Vibroweb (online CMS) multi-channel FFT data collection.	0.1Hz – 45kHz	System is certified by GL.
31	Oil Health	Atten2	Spain	Oil degradation measurement performed by relating specific physic-chemical parameter changes to the formation of polymeric molecules.	Gearbox	On-line spectrometric analysis of oil (rather than debris count)			Not specific to wind industry. Tested on Gamesa and Acciona turbines.
32	MetalSCAN	WindPower Renewable Solutions	UK	Detection of both ferrous and non-ferrous particles from gearbox damage. Sensor placed in-line before the main filter and measures particle count through use of disturbance to applied magnetic field	Gearbox	Inductive based oil debris monitoring system	Particle count		Applied to many current technology turbines: Siemens, Vestas, Acciona, REPower, Gamesa, GE, Suzlon, Nordex

33	MHC (Machine Health Checker)Acoustic Emission System	Kittiwake Holroyd	US/UK	The AE sensor design uses a novel, very stable and reproducible transducer arrangement	Vibration analysis, acoustic emission and oil analysis	Acoustic	Time domain analysis		
34	WINDPCM	Feldman Enterprises	Cyprus/ UK	Monitoring KPIs and using specific alarm thresholds to verify severity of damage detected. Can provide reliable diagnosis	Gearbox, main bearing and generator. Application to other rotating machinery of the WT possible	Integrated acoustic emission and vibration analysis system capable of incorporating oil analysis input using one debris particle sensor	Peak-peak, spike energy, Cepstrum, RMS, signal envelope, FFT, signal normalisation	500kHz for AE, 25kHz or 50kHz for vibration analysis, 1kHz for oil analysis if present	Developed and successfully demonstrated in the field during the NIMO projects. Certification pending. 4-5 AE, 8-10 accelerometers. Oil particle and moisture sensors can be integrated as options.
35	Watchman	Azima DLI	US		Vibration analysis				
36		Bosch	Germany		Vibration analysis				
37	Techalert	Macom	UK	See item 18 – duplicate, delete this one?	Oil particle analysis				
38	OneProdWind	01dB	France	See item 7 – duplicate, delete this one?					
39	MDI Wind (Machine Diagnostic Interface)	Thyssen Krupp	Germany	The primary characteristic to be monitored is the structure-borne noise of the power train – consisting of main bearing, gear unit and generator – as well as key temperature values. The vibration of the nacelle – and of the tower, if required – is also captured. Other monitoring tasks can also be integrated into the system as options	Rotor bearing gear unit, gear bearing, generator, bearing and nacelle	Vibration Oil quality monitoring Torque measurement Tower vibration monitoring Rotor blade monitoring Rotor shaft misalignment	Envelope analysis		

40	Intellinova	SPM	Sweden	The Intellinova system is centred around the Commander Units, each unit serving up to 32 channels for shock pulse, vibration and/or analog measurement in a user defined combination. A dedicated communication software triggers, controls and filters measurements and data, and handles all messaging between the database and one or more Commander Units. Intellinova is a workhorse and the ideal online condition monitoring solution for standard and high-demanding industry applications.	Gearbox (including planetary)	Shock pulse Vibration Analogue measurement	RPM based sampling frequency	Up to 32 channels; user defined	
41	Condition Diagnostics	Winergy	Germany	See item 5 – duplicate, delete this one?					
42	Bladecontrol	IGUSITS	Germany	See item 19 – duplicate, delete this one?					
43		D2S	Belgium		Vibration analysis				8 channels
44		INDRA	Spain		Integrated CMS including vibration analysis, temperature, parametric readings				
45	Ingesys IC3	INGETEAM	Spain		Integrated CMS including vibration analysis, temperature, parametric readings				Multi-channel
46*+	System 1	Bently Nevada (GE)	USA	Monitoring and diagnostics of drive train parameters such as vibration and temperature. Correlate machine information with operational information such as machine speed, electrical load and wind speed.	Main bearing, gearbox, generator, nacelle. Optional bearing and oil	Vibration (accelerometer)	FFT frequency domain Acceleration enveloping	-	

					temperature.				
47+	Condition based monitoring system	Bachmann Electronic GmbH	Austria	Up to nine piezoelectric acceleration sensors per module. Basic vibration analysis with seven sensors. PRÜFTECHNIK solid borne sound sensors used for low frequency diagnostics of slowly rotating bearings on the WT LSS. Three channels for the ±10V standard signal per module. Fully integration in Bachmann's M1 automation control system.	Main drive train components Generator	Vibration (accelerometer)	Time domain FFT frequency analysis	24-bit res 190kHz sample rate per channel	

* Analysis of existing systems undertaken by (Crabtree, 2010) as part of the SUPERGEN Wind Energy Technologies Consortium.
+ Analysis of existing systems undertaken by (Tavner, 2012), which extended upon previous work completed as part of SUPERGEN.

8. Importance of condition monitoring for wind turbines

Wind turbines like all systems operating in adverse conditions may and will normally develop certain types of faults over time. It is important to recognise the criticality of the main components which are needed for the wind turbines to operate correct. Certain components may not be easily replaceable, others may fail more often but result in small downtimes and may be less expensive to replace than repair while some may fail more rarely but result in significant maintenance costs and downtimes.

Over recent years, there has been much effort expended on understanding the reliability of wind turbines, with a focus on the development of improved O&M procedures to reduce the overall cost of wind power. Figure 3 details some of the failure rates and related downtimes for selected wind turbines, which were collected for onshore turbines during two German research programmes. From this, it is evident which systems significantly affect turbine availability.

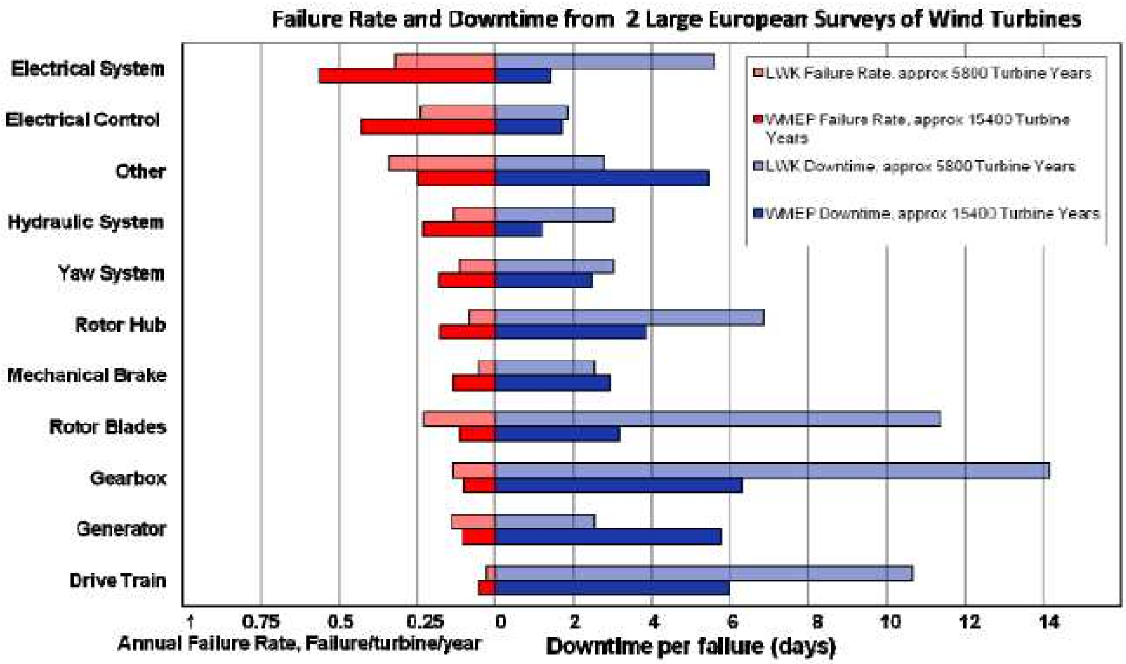

Figure 3: Failure rate and turbine downtime for LWK and WMEP research efforts (Crabtree C. F., 2010).

From the graph in 3 it is possible to infer the total downtime in days/year/turbine for both projects (Figures 3 and 4) that can be attributed to failures and subsequent unscheduled maintenance. It is therefore possible to estimate the average turbine "Technical Availability (γ')" for the turbines in these surveys. The Information Categories referred to in the calculation are taken from IEC 61400-26-1 (IEC, 2011).

$$\gamma' = 1 - \frac{Downtime}{365}$$

$$\gamma' = 1 - \frac{(IANOPCA + IANOFO)}{365}$$

$\gamma'_{LWK} = 97.3\%$

$\gamma'_{WMEP} = 98.2\%$

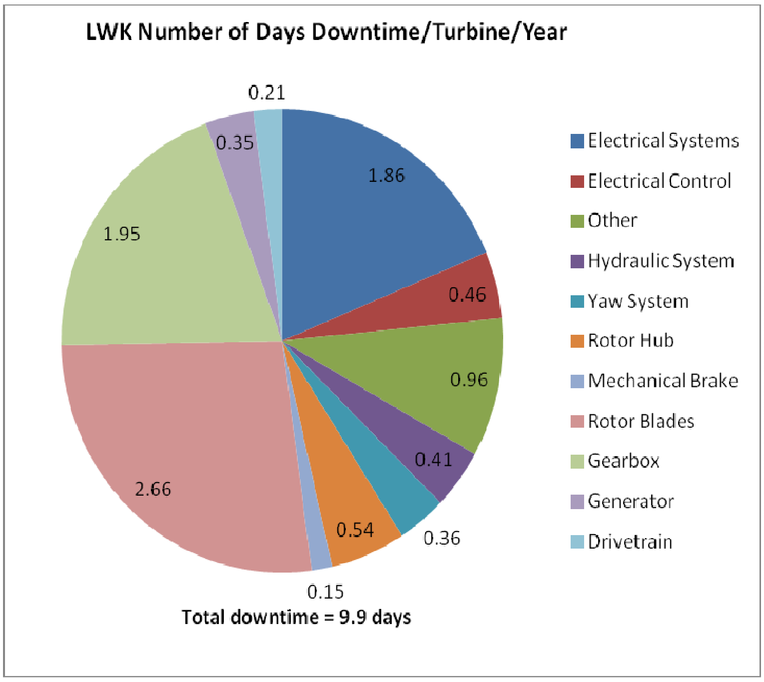

Figure 4: Proportion of downtime per system for LWK programme.

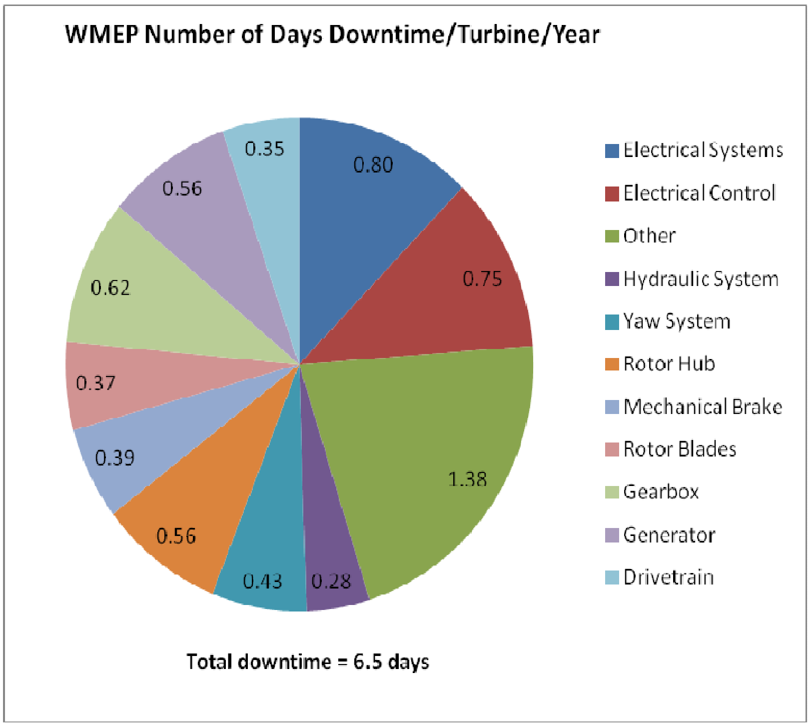

Figure 5: Proportion of downtime per system for WMEP programme.

This calculation assumes that only Planned Corrective Action (IANOPCA) and Forced Outages (IANOFO) have contributed to the data collected within LWK and WMEP databases; i.e. scheduled maintenance does not contribute to the total downtime. Furthermore, the calculation for γ' does not exlude the Scheduled Maintenance, Suspended, Force Majeure or Information Unavailable categories as suggested in IEC 61400-26-1 (IEC, 2011), hence the denominator takes the value of 365 days, rather than being calculated as for γ below:

$$\gamma = 1 - \frac{(IANOPCA + IANOFO)}{\begin{pmatrix} IAOGFP + IAOGPP + IAONGTS + \\ IAONGEN + IAONGRS + IAONGEL \end{pmatrix} + (IANOPCA + IANOFO)}$$

As such, the stated values for γ' are understood to be higher than the actual Technical Availability according to EIC 61400-26-1, however they do provide a realistic approximation to availability. Calculating "Technical Availability" according to IEC 61400-26-1 (IEC, 2011) enables a comparison between turbine availability across various research programmes.

Turbine types – as the data is collected from unknown wind farms (and therefore the type and number of turbines analysed for failure rates are unknown), any serial turbine faults could skew the data; thus may not realistically represent wind turbine failures in general.

Turbine farm location – it is possible that dependent upon wind turbine location, the wind conditions could have an effect on failure rates. For example LWK collected data from wind turbines in the Schleswig-Holstein area of Germany, which is known to have high wind speeds. This may have resulted in a predominant failure method for turbines monitored within this program.

Failure data collection methods – "Other" contributes a significant proportion of turbine failure rate, particularly for WMEP. In conversation with the project lead for WMEP, it is apparent that the failure reporting system was not strictly adhered to, thus there is some unknown information that cannot be apportioned to a particular cause of failure. This unknown data makes up a significant proportion of the data, between 5% and 15% of total turbine downtime.

Maintenance – There is no reported analysis on the scheduled maintenance regimes undertaken for the turbines within the research programs. It is suggested that this can make a significant difference to the frequency and cause of turbine failures. Without knowing the maintenance regimes, this introduces further uncertainty into any conclusions that can be drawn from the pre-existing data.

Cost of O&M – Cost data was asked for within the WMEP program, however it was very rarely reported for commercial reasons. If available, a good understanding of cost reductions from condition monitoring systems could be developed.

North Hoyle wind farm OWCGS Reports ((NPower Renewables Ltd, 2005), (NPower Renewables Ltd, 2006), (NPower Renewables Ltd, 2007)) suggest that O&M activities cost approximately £2.5m-£3m per year within the first three years of operation. It should be noted that this represents operation during the turbine warranty period, where service and repairs relating to the wind turbines is covered by the OEM. As such, this figure is assumed to be low, considering that a third of turbines had major gearbox faults and half of the turbines had experienced yaw motor failures.

It is understood that the cost relating to O&M activities will generally be regarded as commercially sensitive and thus will not often be reported. In order to optimise O&M activities, either reliable data is required from opeating turbines, or reasonable assumptions need to be made regarding the cost of repair/replacement of major turbine components.

CM has become gradually more important in the operation of WTs. Insurers by default require the presence of a certified CMS installed on a WT before they accept to insure it. The insurance of WTs is becoming more demanding as failure rates are costing insurance companies a significant amount of money. Allianz, one of the biggest insurance companies in the world insuring wind turbines, received 1,000 claims from wind turbine operators in 2006 alone. In the foreseeable future insurance companies will demand to know from the wind turbine operators what where the CM data acquired prior to failure, how the operator handled the data and what was their response to this information.

It is generally accepted that CM value will grow in the future for the wind industry but it still has a significant way to go before it can achieve the required reliability. This is particularly true in gearbox CM where the results have sometimes been proved to be questionable or even unreliable. There are several manufacturers of CMS as discussed earlier, with several of them based in Europe.

Improvement in CM efficiency can help WT operators to plan maintenance tasks in low-load seasons where wind energy produced is expected to be at its lowest thus resulting in minimum financial losses. Also effective CM should enable the reduction of the frequency of service interruptions and undesirable consequences these interruptions are associated with. Efficient and reliable CM can contribute in the reduction of personnel required for regular onsite inspections as well as ensure that the required spare parts are available in time for repairs minimising delays.

When considering offshore WTs accessibility may be extremely restricted particularly during winter time. Thus the cost of maintenance tasks can increase substantially because of the remoteness of the location of offshore wind farms as well as due to accessibility issues and the requirement of special equipment. Failure of critical components, particularly gearboxes and power converters during peak production season could have extremely negative results for the financial success of an offshore wind farm project.

The effect of sudden failure in comparison to planned maintenance in overall maintenance cost can be visualised in the plot reported by Bachmann. It is evident that unexpected failure can result in substantial unnecessary costs which can be prevented by the application of an efficient and cost-effective CMS.

Effective maintenance strategies should aim to reduce the frequency of service interruptions and the undesirable consequences of such interruptions, e.g. loss of energy production. The maintenance strategy affects item and system reliability in a way that if too little maintenance is performed, i.e. the system is returned in an 'as good as operating' condition, then this may result in an excessive number of costly failures and poor system performance, which in turn results in the system reliability being degraded.[23,24,3] However, if maintenance tasks are performed too often, reliability may improve but the cost of maintenance will increase substantially.[3,24] Therefore a cost-effective maintenance strategy optimisation involves balancing the cost of maintenance tasks and system reliability.[23]

The main purpose of maintenance optimisation for power plants is to determine the most cost-effective maintenance strategy, which will provide the best possible balance between direct maintenance costs, e.g. labour, resources, materials and administration costs, and the consequences or penalty of not performing maintenance as required, e.g. loss of production and anticipated income and profit.[16,25] When considering the maintenance strategies then three categories can be used known as the reliability-centered maintenance, the total-productive maintenance and risk based maintenance:

- **Reliability centred maintenance.** This technique is used to optimise the practices of the maintenance strategy in order to prevent the reliability level of the system from dropping below a certain specified value at any means.[26,1] This approach is based on achieving a level of reliability for the items/parts required at any maintenance cost. This technique is employed for items/parts that are critical for the operation of the system, or their failure could result in catastrophic system failure or high loss of revenue.

- **Total productive maintenance**. This technique is a critical addition to lean production, where the maintenance tasks and operations are designed to achieve the desired goal, e.g. high production or low cost.[1,3,24] This maintenance optimisation is based on a combination of preventive maintenance actions and continuous efforts to modify and redesign equipment and techniques with a goal to increase flexibility in processes and promote higher yield in production.[1]

- **Risk based maintenance.** It aims at reducing the overall risk of failure of the operating facilities. In areas of high and medium risk, a focused maintenance effort is required, whereas in areas of low risk, the effort is minimized to reduce the total scope of work and cost of the maintenance program in a structured and justifiable way.

The possible maintenance strategies for offshore wind farms are listed below:

1. **No maintenance strategy**: Neither preventive nor corrective maintenance are performed on the offshore wind turbines but only major overhauls are performed between long periods of time, e.g. 5 years. This maintenance strategy could be a possible solution when the failure rates of offshore wind turbines are very low. Considering the current reliability of existing offshore wind turbines this strategy cannot yet be implemented; it could only form a possible solution for future highly reliable offshore wind turbine designs.

2. **Corrective (breakdown or reactive response) maintenance strategy**: Repairs are carried out after an offshore wind turbine has failed, where the maintenance expeditions are initiated immediately provided weather and sea state conditions permit them. This maintenance strategy is the present practice adopted for existing offshore wind farms.

3. **Periodic maintenance or planned intervention maintenance policy**: Fixed dates are set at the duration of the operational year of the offshore wind farm, when maintenance personnel are transferred to the offshore wind farms to repair, replace or inspect the wind turbine components. Preventive and predictive maintenance practices could be integrated into this strategy. Offshore wind turbines could be monitored for

their condition and statistical reliability tools are used to preventively maintain or exchange critical items before any failure occurs. The specific periods for the planned maintenance expeditions could depend on different parameters of offshore wind farms, e.g. weather and sea state conditions, accessibility levels, availability levels, or reliability of wind turbines.

4. **Predictive maintenance:** Carrying out maintenance activities based on prediction of damage evolution and taking into account available resources as well as power production losses. In order to be cost efficient it needs to be accurate and rely heavily on reliable diagnostic data which can also be used for prognosis.

Figure 6 shows the difference in costs between sudden and planned maintenance strategies. In theory if predictive maintenance is carried out efficiently it should result in even further saving than planned maintenance.

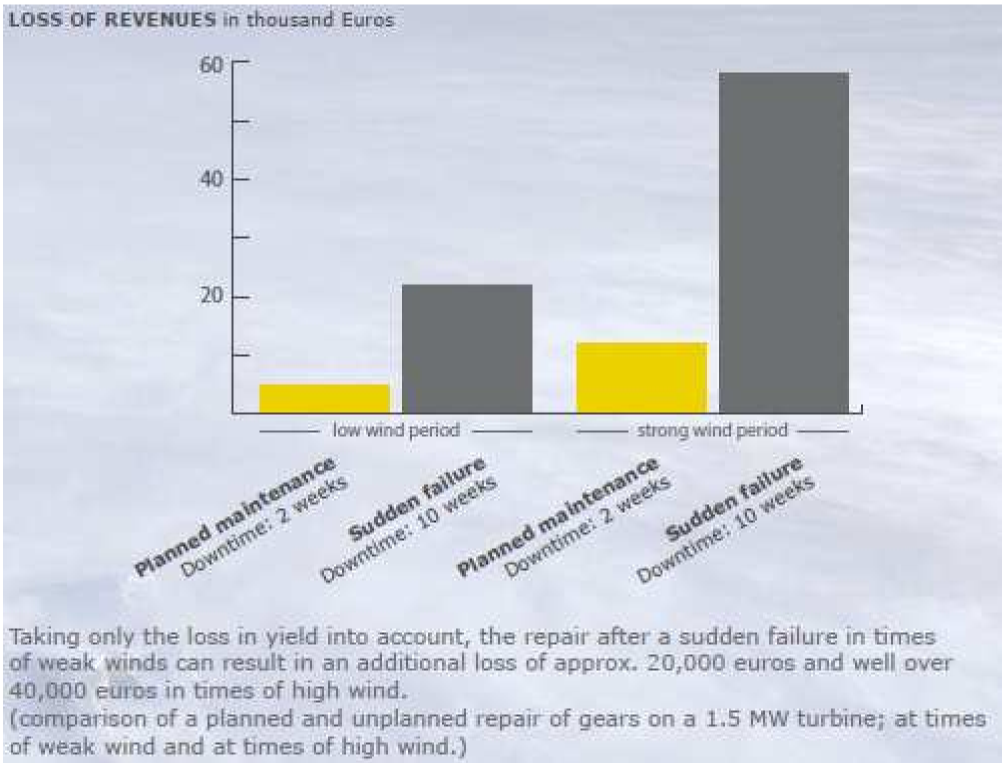

Figure 6: Loss of revenues arising from sudden failure in comparison to planned maintenance depending on the period that failure takes place. Data have been reported by Bachmann Gmbh.

9. Conclusions

In this report the information available on existing commercial, pre-commercial and research based condition monitoring systems has been collected by the consortium and summarised in this report. The systems and techniques used by the industry have been presented and the importance of prognostic maintenance has been emphasised in comparison with corrective maintenance strategies commonly employed by several wind farm operators. The operational requirements set by wind turbine manufacturers and operators for the minimisation of occurrence of faults and failures have been assessed and are presented in this report. The efficiency and reliability of existing systems has been compared with the operational requirements as these have been set by wind turbine operators and manufacturers in order to optimise wind turbine operation. The results of the present deliverable report have been considered and analysed by the consortium in order to ensure that a substantial step-change in the efficiency and reliability of wind turbine operation will be realised and demonstrated by the end of the OPTIMUS project.

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